Wyoming Level II
Weather Modification
Feasibility Study

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3 March 2005

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BACKGROUND AND INTRODUCTION

In the spring of 2004, the Wyoming Water Development Commission (WWDC) issued a request for proposals for a Level II Weather Modification Feasibility Study. After a competitive screening process, the WWDC awarded the study to Weather Modification, Inc. (WMI) of Fargo, North Dakota. The RFP required the study of two possible target areas within the State of Wyoming: the Wind River Mountains in west-central Wyoming, and the Medicine Bow and Sierra Madre Mountains in the southeast.

The feasibility study enumerated fifteen specific tasks, listed below:

1.   Scoping and project meetings
2.   The review of related data previously collected in Wyoming and/or relevant to Wyoming
3.   Study of the climatology of the proposed target areas
4.   Preliminary project design
5.   Establishment of operations criteria
6.   Summary of environmental and legal issues
7.   Permitting and reporting requirements
8.   Site access and easements
9.   Evaluation methodology
10.   Potential benefit and hydrologic assessment
11.   Cost estimates
12.   Preliminary benefit-to-cost analysis
13.   Reports and executive summaries
14.   Presentations and public hearings
15.   Monitoring of study areas

Each of these tasks is addressed in this report in sections numbered accordingly.

The notification to proceed was given to WMI by the WWDC on 26 June 2004. Scientists within the Research Application Laboratory (RAL) at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado were engaged as subcontractors to assist with the modeling of the complex terrain, and also with the development of the preliminary project design, the evaluation methodology, and assessment of the potential benefits and hydrology.

Since that time, work has been ongoing. The original timeline proposed by WMI is shown below (Figure 0.1). The first task proposed was to conduct scoping and other project-related meetings at various locations throughout the state engaging the various stakeholders. Because of schedule conflicts, however, these meeting could not be conducted with participation of all the interested parties until mid-August (see Section 1).

WMI / NCAR Timeline for Wyoming Feasibility Study

	June	July	August	September	October	November
Task 1	Scoping and Project Meetings					
Task 2	Review & Summarization of Previous Data					
Task 3	Climatology of the Project Areas					
Task 4	Development of Prelim. Proj. Design					
Task 5	Establishment of Ops. Criteria					
Task 6	Environmental and Legal Considerations					
Task 7	Permitting and Reporting					
Task 8	Access and Easements					
Task 9	Evaluation Methodology					
Task 10	Potential Benefits/Hydrologic Assessment					
Task 11	Cost Estimates					
Task 12	Preliminary Cost-Benefit Analysis					
Task 13	Reports and Executive Summaries					
Task 14	Project Presentations & Public Hearings					
Task 15	Climatological Monitoring of Study Areas					
Task 16	Trace Chemistry Studies					

WMI Task
NCAR Task
Joint Task

Figure 0.1 - The original timeline proposed for the Level II Feasibility Study.

Task 16, Trace Chemistry Studies, was proposed as a supplemental task by WMI, but was not funded due to lack of resources. Nevertheless, WMI believes this to be important and suggests that this still be done prior to the onset of operations (See Section 15).

The fact that the scoping meetings were not conducted until mid-August 2004 did not preclude the initiation of work on tasks 2, 3, 6, 7, 8, 9, and 10, however. Thus, though work commenced later than the planned 15 June 2004 start date, less than two weeks was actually lost.

The balance of this report is devoted to summarizing the various tasks and where appropriate, providing information regarding work still ongoing (Task 15) and other relevant work yet to be accomplished.

1.   SCOPING AND PROJECT MEETINGS

Task One of this feasibility study was comprised of a series of meetings with representatives of various Wyoming state agencies, conservation districts, the U.S. Forest Service, the Bureau of Land Management (BLM), the National Weather Service (NWS), and others.

Because of conflicts between the schedules of the WWDC and WMI staff, and to a lesser degree the availability of meeting rooms, these meetings could not be scheduled until mid-August rather than late June.

1.1   17 August 2004, Cheyenne

The first meeting took place at 08:00 MDT in the WWDC offices in Cheyenne. Making presentations on behalf of WMI were Director of Meteorology Bruce Boe (M.S. University of Wyoming 1981), and Dr. James Heimbach (Professor Emeritus, University of North Carolina at Asheville). Representing NCAR was Dr. Roelof Bruintjes, Senior Scientist, Research Applications Laboratory.

The WWDC was represented by Barry Lawrence, and the Wyoming State Engineer's Office by Leah Bratton. The Wyoming State Engineer's Office is the permitting entity for weather modification (cloud seeding) activities in the State of Wyoming.

The audience was comprised primarily of staff from various state and federal agencies, as shown in Table 1.1.

Table 1.1 - Attendees of 17 August 2004 Cheyenne Weather Modification Meeting			
Name	*Agency*	*Name*	*Agency*
Greg Kerr	U.W. Civil Engineering	Jeremy Lyon	Dept. Environmental Quality
John Barnes	State Engineer's Office	David Copley	National Weather Service
Jan Curtis	Wyoming State Climatologist	Bill Parker	National Weather Service
Hugh McFadden	Attorney General's Office	David Zelenka	WWDC
Ken Schultz	Wyoming Dept. Transportation	Jane Caton	Attorney General's Office
Susan Child	Office of State Lands	Chris Abernathy	WWDC
Sue Lowry	State Engineer's Office	Phil Stump	State Engineer's Office
James Uzzell	Dept. Environmental Quality	Jodie Pavlica	WWDC

The meeting began with introductions followed by a PowerPoint overview of the feasibility study by Barry Lawrence. After Mr. Lawrence had completed his presentation, Leah Bratton of the Wyoming State Engineer's Office spoke about regulation of weather modification in Wyoming and the requirements for permitting through the Wyoming State Engineer's Office. Ms. Bratton was followed by Bruce Boe who reviewed WMI's perspective of the study and progress to date. Dr. Heimbach then summarized the Bridger Range Cloud Seeding Experiment conducted in neighboring Montana. Heimbach reported that the winter orographic cloud seeding program had been very successful and had been subjected to both statistical and physical evaluations. The Bridger Range is located just north and east of Bozeman, Montana.

The formal presentations were concluded by Dr. Bruintjes, who spoke to the relevance and role of various atmospheric aerosols, and then on the detailed modeling began by NCAR using the state-of-the-art Weather Research and Forecasting (WRF) model. Bruintjes noted that evidence is mounting suggesting that the atmospheric aerosols responsible for cloud and precipitation formation are changing with deleterious effects upon precipitation, probably

globally. Weather modification by cloud seeding, he said, may offer an opportunity to correct these unnatural changes.

Discussion followed, during which Jan Curtis offered some constructive comments and provided two copies of the recently completed Wyoming Climate Atlas authored by himself and Kate Grimes.

Concern was expressed about possible negative effects (increased closures) if Interstate Highway 80 is closed between Laramie and Rawlins during winter storms. Boe offered that seeding suspension criteria and numerical modeling efforts might mitigate any potentially negative effects in that regard.

The entire meeting lasted about 2.5 hours.

1.2   17 August 2004, Saratoga

The second meeting took place at 15:00 MDT in a meeting room in Saratoga, Wyoming, between the Medicine Bows and the Sierra Madre Mountains. Presentations were made in the same order as in Cheyenne by the same individuals.

At this meeting, the audience was comprised of conservation district members and staff from various state and federal agencies as shown in Table 1.2.

Table 1.2 - Attendees of 17 August 2004 Saratoga Weather Modification Meeting				
Name	*Agency*		*Name*	*Agency*
Dave Taylor	NRCS, Casper		Jeb Steward	Saratoga Encampment Rawlins Conservation District (Chairman)
Brad Holliday	Medicine Bow Conservation Dist.		Buck Buchanan	Saratoga Encampment Rawlins Conservation District
Carol Purchase	U.S. Forest Service		Glen Leavengood	Saratoga Encampment Rawlins Conservation District
Joe Glode	Upper N. Platte Water Users		John C. Bellamy	(former Dept. Head, NRRI)
Robert Kelly	Watershed Protection Committee, Encampment, WY		Jon Wade	WWDC
Mike Snigg	Wyoming Game & Fish Dept.		John Jackson	WWDC

The meeting again began with introductions followed by the same presentations by the same individuals as in Cheyenne earlier that morning. Discussion followed, during which Carol Purchase offered some perspective from the Forest Service viewpoint. She noted that very specific rules exist regarding placement of facilities of any type in wilderness areas.

The meeting lasted a little more than 2.5 hours.

1.3   18 August 2004, Eden Valley Irrigation District, Farson

On the morning of 18 August, the WWDC, WMI and NCAR staff drove from Rock Springs up to Farson, where the offices of the Eden Valley Irrigation District (EVID) are located. The EVID is the only entity presently actively seeding clouds in Wyoming on an annual basis. Each winter,

from 15 November through 30 April, the EVID uses three ground-based cloud seeding ice nuclei generators to seed clouds upwind of the southern Wind River Mountains. These generators are placed at 10 mile intervals along U.S. Highway 191 north of Farson. These generators (see Figure 1.1) which burn a silver iodide solution are complemented by two additional high-altitude propane ice crystal generators. While the generators along Highway 191 are operated manually by EVID staff, the propane generators are remote controlled and operated by the Provo, Utah office of the Bureau of Reclamation. Operations data for the latter generators were requested from the Provo office by WMI immediately following the scoping meetings, but were not received until 18 October 2004.

Figure 1.1 - A manually-operated silver iodide generator of the type used along Highway 191 (Photo courtesy of R. Bruintjes, NCAR).

The EVID program was designed by the University of Wyoming's Department of Atmospheric Sciences, and for a time, also operated by the Department. However, the program is presently operated independently by the EVID, and the Wyoming State Engineer's Office issues the operations permit annually to the irrigation district itself.

Operations have been conducted annually since 1975. The irrigation district believes it realizes an 11% to 13% increase in snowfall (water equivalent) as a result of the seeding operations.

1.4   18 August 2004, Pinedale

The third scoping meeting took place at 13:00 MDT in the Sublette County Public Library meeting room. At this meeting, the audience was comprised of members of the Eden Valley Irrigation District, a reporter, and staff from various state and federal agencies as shown in Table 1.3. In addition to those shown below, Mr. Terry Svalberg of the U.S. Forest Service stopped prior to the meeting and provided a copy of the Forest Service regulations governing the placement of seeding generators in wilderness areas. Unfortunately, Mr. Svalberg had another commitment and could not stay for the meeting itself.

Table 1.3 - Attendees of 18 August 2004 Pinedale Weather Modification Meeting				
Name	*Agency*		*Name*	*Agency*
Floyd Field	WWDC		Chris Harns	Eden Valley Irrigation Dist.
Kierson Crume	BLM, Pinedale Field Office		Bonnie Moody	Eden Valley Irrigation Dist.
Mary Gamper	BLM, Pinedale Field Office		Jon Wade	WWDC
Cat Urbigkit	Sublette County Examiner		John Jackson	WWDC

The meeting again began with introductions, followed by the same presentations by the same persons as in Cheyenne and Saratoga the day before.

Interest was expressed by the EVID staff members and the BLM staff. This meeting lasted nearly three hours.

After the meeting in Pinedale, the WWDC, WMI, and NCAR staff drove a rather circuitous route over Union Pass on the northern end of the Wind River Range itself. The drive was well worth it, as a good feel for the character of the northern end of the Wind River Range was obtained. The highest terrain was south of the path driven, but even so, several broad high-elevation mountain meadows were observed along with a variety of wildlife. After about 2.5 hours, most of it spent in the rain, the group reached Dubois where the final scoping meeting was scheduled for the following morning.

1.5   19 August 2004, Dubois

The fourth and final scoping meeting took place at 10:00 MDT at the Headwaters Arts and Conference Center in Dubois.

For the first time, tribal interests were represented at this meeting. The audience is listed in Table 1.4. In addition, Joe Sullivan, Meteorologist-In-Charge (MIC) of the Riverton Weather Service Office, was also present. The series of presentations were repeated once again.

The discussion was lively with many questions, especially from the two members of the Joint Wind River Tribal Water Board present. Gary Collins, one of the Water Board's technically expert staff, expressed interest on the part of the Water Board. As a result, Boe was invited to Fort Washakie for that Board's next scheduled meeting on 1 September 2004.

Table 1.4 - Attendees of 19 August 2004 Dubois Weather Modification Meeting				
Name	*Agency*		*Name*	*Agency*
Floyd Field	WWDC		Lee Arrington	Midvale Irrigation District
Joe Sullivan	National Weather Service, Riverton		Aaron Marshall	State Engineer's Office
Terry Henderson	Bureau of Indian Affairs		Jon Wade	WWDC
Gary Collins	Office of Tribal Water		John Jackson	WWDC

	Board		
Judi Mott	BLM	Pete Calhoun	Office of Tribal Water Board
Mark Hinschberger	USDA Forest Service		

Much time was devoted to discussing the importance of tribal support of any Wind River program owing to the Wind River Indian Reservation's large area and location. The meeting concluded during the noon hour and the participants went their separate ways. Follow-up between Boe and Collins confirmed the invitation to address the Joint Tribal Water Board on 1 September, and Sullivan also invited Boe to make a presentation to the Riverton Weather Service Office during that same time frame.

1.6   31 August 2004, National Weather Service, Riverton

On 31 August 2004, Boe flew to Riverton (RIW) via Denver and spoke that afternoon to the staff at the RIW Weather Service Office. It was a very clear day throughout Wyoming so attendance was good. Meteorologist In Charge (MIC) Joe Sullivan had extended the invitation but had to be in Boulder that day and so was not present. In addition to the duty forecasters and two interns, the Science Operations Officer (SOO) and Warning Coordination Meteorologist (WCM) were present. All were interested in Boe's presentation about the feasibility study, and there were many questions and suggestions. Interaction continued for about 90 minutes, after which additional time was spent with the SOO and WCM examining various data sources—paper and on-line. The visit was very productive, and Boe reported learning much about the regional climate.

1.7   1 September 2004, Tribal Water Board, Fort Washakie

On 1 September, Boe was picked up in Riverton by Barry Lawrence and John Jackson of the WWDC and they drove over to the office of the Joint Tribal Water Board (Eastern Shoshone and Northern Arapaho) in Fort Washakie. The Water Board began to gather at about 13:00 local time and the meeting itself began at about 13:20. Gary Collins, the Board's technical person, had prepared the agenda and led discussion on all technical matters. The Board was very interested in the technology and its potential to bring more water to the reservation. Assurances were sought that if the tribes support a program, the portion of the Wind Rivers upwind of the reservation would be given the same treatment as other areas.

The Board was assured unequivocally by Boe and the WWDC staff that all will be treated equally. The Chair of the board asked Boe and the WWDC staff if they had spoken to the Tribes' Combined Business Council, and were told that they had not. Being that cloud seeding is a water management tool, Boe said, he thought it best to speak to the Combined Water Board first and that it would be up to the board if they thought a presentation should be made to the Business Council. As this study was completed, no presentation had yet been made to the Business Council, but dialog with the tribes continues.

2. REVIEW AND SUMMARY OF PREVIOUS DATA

Because of Wyoming's rich history in weather modification research, Task Two was established to review this work and integrate it with other relevant work to establish the scientific basis for the proposed Wyoming winter orographic programs. Considerable effort was spent in literature review, not only in the published, refereed publications such as the journals of the American Meteorological Society, but also reports, theses, and dissertations produced at the University of Wyoming (UW) Department of Atmospheric Science (DAS). The results of this review are summarized in this section. Complete references are supplied in Section 16 so that anyone wishing to review in detail the sources cited can do so.

A significant focal point of the UW DAS research has been the research laboratory located atop Elk Mountain just south of I-80 on the north end of the Medicine Bow Range. Summaries of the most notable publications follow.

2.1 Observations of Ice Crystal and Ice Nuclei Concentrations in Stable Cap Clouds

A total of 88 observations of ice crystal concentrations and ice nuclei concentrations (as measured by an NCAR acoustic ice nucleus counter) were made at the Elk Mountain Observatory and correlated with observed ice crystal habit (shape) by Auer et al. (1969). A temperature dependence was observed wherein colder clouds tended to contain more ice. However, the colder clouds did not necessarily contain more ice nuclei. The authors were unable, however, to identify any ice multiplication mechanism that could explain the observations.

2.2 An Investigation of Liquid Water-Ice Content Budgets Within Orographic Cap Clouds

Observations within cap clouds at the Elk Mountain Observatory revealed that the differences between the adiabatic liquid water content and the observed liquid water content closely approximated the ice content of the cap clouds (Auer and Veal 1970). These observations are helpful in that they help verify our understanding of the cloud processes that produce orographic clouds.

2.3 Some Observations of Silver Iodide Plumes Within the Elk Mountain Water Resource Observatory

Observations of silver iodide ice nuclei plumes over Elk Mountain revealed that in stable (non-convective) conditions, the plumes seldom mixed to heights greater than 450 m (1,500 ft) above the surface and that the dispersion angle of said plumes was about 10 degrees (Auer et al. 1970). Concentrations of ice nuclei within the plume, some 10 to 17 km downwind of the seeding generator, varied from a few nuclei per liter at the edges of the plume to maximum observed concentrations of about 150 per liter. These early observations are in general agreement with those made more recently over the Grand Mesa of Colorado (Super and Boe 1988).

2.4   Cloud Droplet Concentrations and Cloud Condensation Nuclei in Elk Mountain Cap Clouds

Droplet concentrations predicted from cloud condensation nuclei (CCN) spectra, using the model of Young (1974), were almost always greater than the observed concentrations, but 75% of the calculated concentrations were within one standard deviation of the mean measured droplet concentrations. The trend of the predicted concentrations over periods of about seven hours correlated reasonably well with the observed droplet concentrations if allowance was made for the finite parcel transit times between the CCN sampling site and the Elk Mountain Observatory where droplet spectrum measurements were made. It therefore appears possible to predict an upper limit for the droplet concentrations in winter clouds (Black 1980).

2.5   The Origin of Ice in Mountain Cap Clouds

Ice crystal development in simple layer (cap) clouds was studied using airborne instrumentation (Cooper and Vali 1981). These observations suggest that ice originates in association with the initial condensation process near the upwind edge of the cloud. Since continued ice production does not appear to continue beyond the edge of the cloud, the initial ice formation can be attributed to nucleation. No evidence was found for secondary ice production. Ice crystal concentrations showed a clear inverse relation with temperature as expected for nucleation processes.

2.6   The Possibility of Collision Nucleation by an AgI Aerosol in an Orographic Cap Cloud

Ice crystals having frozen cloud droplets as their embryos were studied at the Elk Mountain Observatory (Davis and Auer 1972). The study found that the number of ice crystals possessing frozen droplet embryos increased considerably during seeded periods.

The likely number of collisions between AgI ice nuclei and cloud droplets was calculated using thermal coagulation theory, known Elk Mountain plume dispersion characteristics and the characteristics of the seeding aerosol itself. This number was found to be in excellent agreement with the increased number of droplet-embryo ice crystals observed during seeding. This suggests that with the aerosol used, contact-freezing nucleation may be very important in determining the ice crystal production attainable by seeding.

It is noted, however, that the AgI aerosols currently in use function primarily by the condensation-freezing nucleation mechanism (e.g. DeMott 1999) and so the present importance of contact-freezing is considerably diminished.

2.7   The Persistence of Seeding Effects in a Winter Orographic Cloud Seeded With Silver Iodide Burned in Acetone

A single case-study of a winter orographic cloud over the Sierra Nevada was examined (Deshler and Reynolds 1990). The effects of aerial seeding were found to persist for over 90 minutes after the seeding and 100 km (~60 statute miles) downwind of the origin of the seeding line.

This suggests that aerial seeding conducted over the Green River Basin west of the Wind Rivers could persist perhaps as far east as Riverton (not an undesirable effect), and likewise the aerial seeding conducted upwind (west) of the Sierra Madre and Medicine Bows could affect the

those entire ranges. This finding strengthens the case for airborne seeding especially in regions where wilderness may preclude the siting of ground-based facilities.

2.8   The Precipitation Efficiency of Orographic Clouds

Aircraft measurements were taken upwind, over and downwind of the Medicine Bow Range in southeastern Wyoming during the presence of winter orographic cap clouds (Dirks 1973). These measurements were used to calculate the precipitation efficiencies of the subject clouds.

Data from the four case studies reported found efficiencies ranging from 25% to 80%. In all four cases studied the atmosphere was characterized as unstable, meaning convection was possible in all cases.

Dirks concluded that winter orographic clouds over Elk Mountain often have precipitation efficiencies on the order of 50% but acknowledged a "major flaw" in the experimental design resulting from the possible mixing of warm, dry air downward across the inversion into the cloud layer, which could result in both drying and warming of the cloud layer, similar to the effect of precipitation within the layer. Efforts were made to identify and exclude such cases from that study.

2.9   Condensation-Freezing Ice Nucleation in Wintertime Orographic Clouds

Additional microphysical observations of several stable wintertime orographic cap clouds over Elk Mountain were described by Kelly (1978). Kelly reported that ice crystal concentrations rose rapidly within 2 to 3 km of the upwind (leading) cap cloud edge, and increased little, if at all, throughout the remainder of the cloud. This finding is consistent with that previously reported by Davis and Auer (1972), and reinforces the conclusion that secondary ice production and deposition ice nucleation are not major sources of cap cloud ice crystals.

Seeding with glaciogenic (ice-forming) seeding agents upwind of orographic clouds could thus significantly increase ice crystal concentrations, and potentially precipitation, within such clouds.

2.10   Wind Characteristics in Southern Wyoming

Measurements from a network of surface anemometers and a 107 m tower were analyzed for the area north of the Sierra Madre and Medicine Bow Mountains, where topographically-forced channeling of stable air flow regularly occurs across a low region of the continental divide, especially during winter (Martner and Marwitz 1982). These winds are subject to the typical diurnal variation, being stronger near the surface during daylight hours when mixing induced by surface heating occurs.

The wind corridor described by Martner and Marwitz (1982) significantly impacts travel on I-80 because visibility due to blowing snow during winter and wind loading on high-profile vehicles year-around. The Wyoming Department of Transportation informally has expressed concern that cloud seeding should not exacerbate the situation.
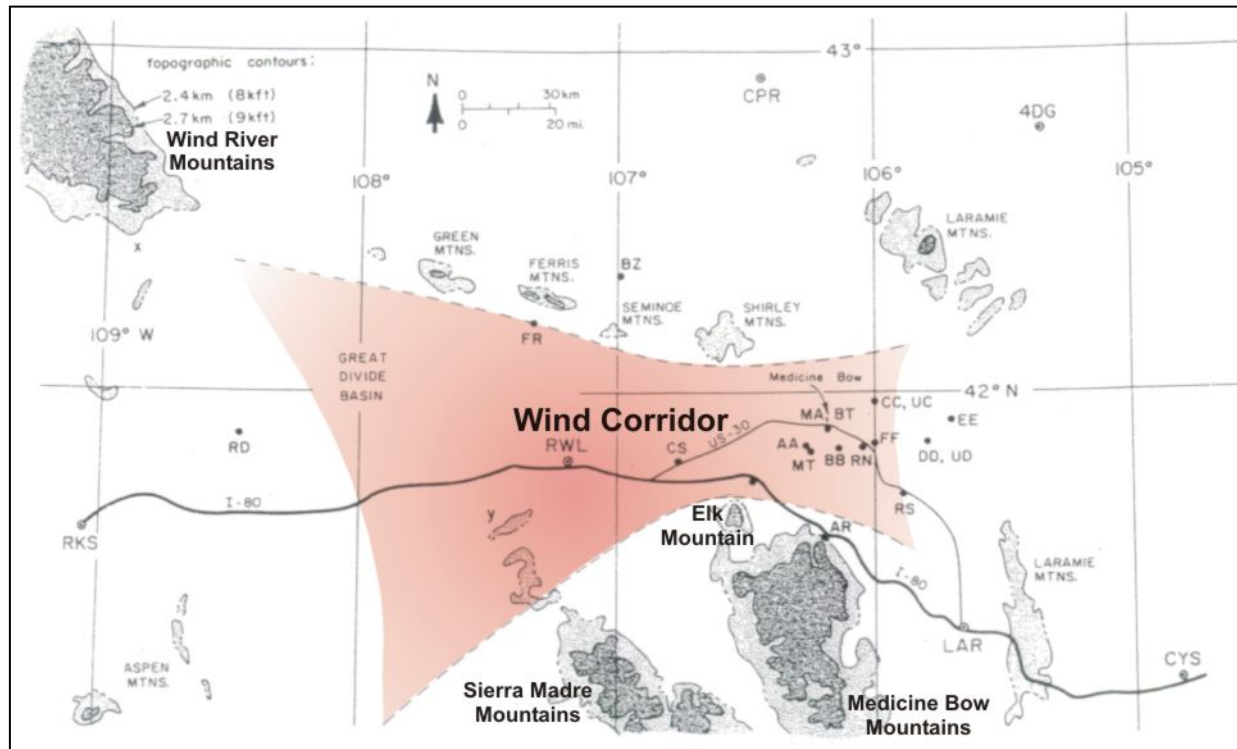
Figure 2.1 - The topographically-induced wind corridor of southern Wyoming modified from Martner and Marwitz 1982. Copyright American Meteorological Society, used by permission.

2.11   Low-Level Airflow in Southern Wyoming During Wintertime

Marwitz and Dawson (1984) followed the work of Martner and Marwitz (1982) with airborne wind measurements in the Wyoming wind corridor using an instrumented aircraft. The later findings corroborated those previously derived with surface-based wind measurements and extended the known boundaries of the corridor some 60 to 70 miles further east to Cheyenne on the southern side, and Laramie Peak on the north.

Though the wind corridor does not generally include the Sierra Madre or Medicine Bow Mountains themselves, its close proximity will require careful siting of any ground-based seeding equipment intended to target these ranges. It is likely thought that any ground-based seeding conducted with ice nuclei generators sited at lower elevations will be subject to the effects of the wind corridor, which logically would include channeling of the seeding plumes to the northeast through the corridor rather than over the mountain ranges as would be desired.

2.12   Observations of Liquid Water in Orographic Clouds Over Elk Mountain

Cloud droplet measurements accrued over a five-year period at the Elk Mountain Observatory were summarized by Politovich and Vali (1983). Droplet concentrations were found to be most often near 300 cm^{-3} owing to the comparatively weak updrafts within the cap clouds and the mid-continental, relatively unpolluted CCN (cloud condensation nuclei) concentrations then prevalent in the region.

It was determined that parcel residence times within the cap clouds typically ranged between 500 to 1500 seconds (8.5 to 25 min), depending upon cloud extent and wind speed. Cloud liquid water contents as great as 1.0 g m^{-3} were occasionally observed; however, the norm was 0.15 g m^{-3} for isolated cap clouds and 0.29 g m^{-3} for broader orographic clouds. The average temperature at which the observations were made was -11.7°C, $\pm 3.0^{\circ}$. The consistent presence of supercooled cloud liquid water at these temperatures indicates a clear potential for glaciogenic seeding.

Additional evidence of the presence of ample supercooled liquid cloud water is shown in Figure 2.2. It shows airframe icing accrued during just two passes through supercooled cap cloud over Elk Mountain in the autumn of 1982.

Figure 2.2 - A rimed strut on the airframe of University of Wyoming cloud physics Beechcraft Queen Air N10UW. The ice buildup occurred on two consecutive passes through the Elk Mountain cap cloud, and was estimated to be about 1.5 to 2.0 inches thick. (The dark band across the center is shadow.) An immediate full-power descent was required to land the aircraft safely back in Laramie. (Photograph courtesy of B. Boe.)

It is supercooled liquid cloud water that results in aircraft icing, not flight through snow, hail, sleet or rain. It is this same supercooled liquid cloud water, not converted to precipitation by natural processes, which can be tapped by glaciogenic seeding to generate additional precipitation. Thus, while undesirable for aircraft, supercooled liquid water is needed in order for glaciogenic cloud seeding to be effective.

2.13   Field and Laboratory Studies of Ice Nucleation in Winter Orographic Clouds

A technique for measuring ice nuclei both below and above water saturation was developed using a continuous flow gradient diffusion chamber (Rogers 1982). Characterizing tests with the chamber were conducted at both warm (+15°C) and cold temperatures with natural air and artificial aerosols. These tests confirm the concepts of chamber operations, particle growth, and optical detection. They also provided the bases for analyzing the data, specifically recognizing the appearance of ice crystals on active nuclei and discriminating these crystals from smaller haze droplets and dry aerosols. Figure 2.3 below compares Rogers' (1982) findings with those of others studying Elk Mountain cap clouds.   A clear dependence on temperature is demonstrated.
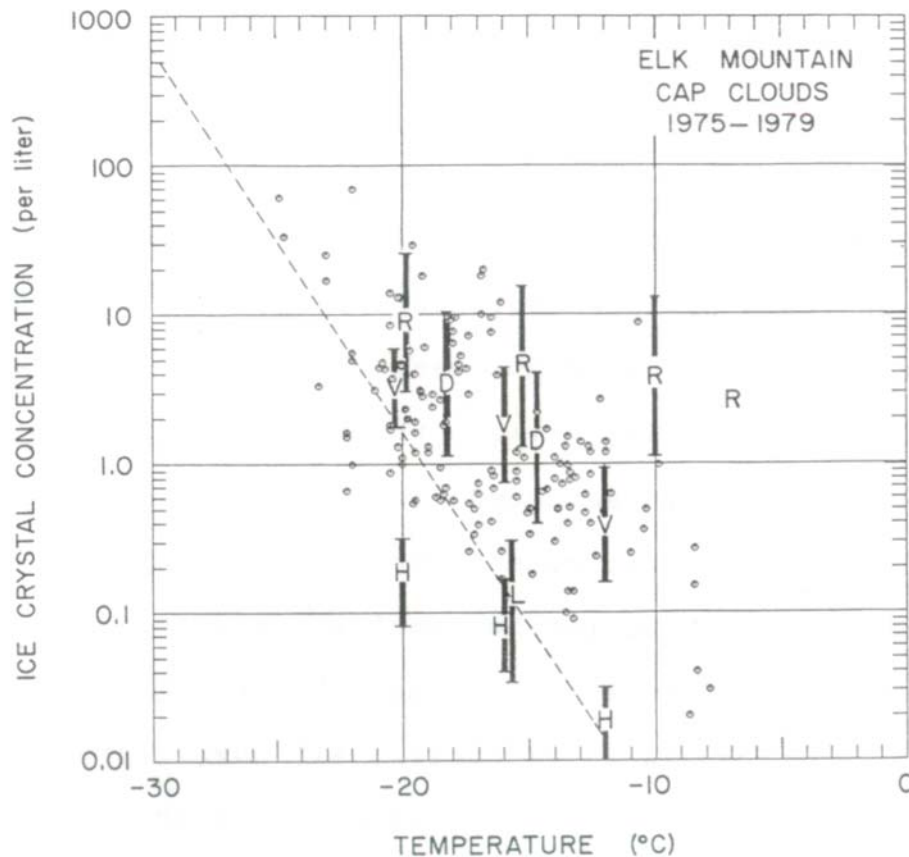
Figure 2.3 - Summary of ice crystal concentration measurements in Elk Mountain cap clouds. Each aircraft data point (circle) represents a cloud penetration average. Data from 30 clouds on 26 days in the period 1975 through 1979 are plotted. Geometric means and standard deviations of ice nucleus data are from (H) Huffman's (1973) and (L) Legg's (1977) membrane filter measurements, from (V) Vali's (1974 and 1976) and (D) Deshler's (1982) contact nucleus measurements, and from the present research (R). Fletcher's (1962) mean ice nucleus curve (dashed line) is also shown for reference. (Figure is from Rogers 1982.)

2.14   Cloud Droplet Measurements in Wintertime Clouds

Airborne measurements of cloud droplet spectra were obtained in five cloud types over the High Plains and mountains of Colorado and Wyoming (Walsh 1977). Additional data were obtained with an impaction sampler and a ground-based Forward-Scattering Spectrometer Probe (FSSP). Typical spectra, with the exception of those observed in the San Juan Mountains, had mean droplet diameters <10 μm. Maximum droplet sizes rarely exceeded 20 μm. Droplet concentrations were usually <300 cm^{-3}, and cloud liquid water contents <0.20 g m^{-3}. The spectra in orographic clouds exhibited longer growth times, which appeared to be associated with broadening of the droplet size ranges and formation of precipitation. The study concluded that knowledge of cloud droplet spectra is important in understanding the cloud processes. The observations made in the context of the study demonstrated that droplet spectra provide good indicators and tracers of a number of cloud processes and are useful in determining cloud origins through their relations to CCN and supersaturation and the formation of precipitation.

2.15   The Eden Valley Irrigation District Operational Cloud Seeding Program

In the early 1970s, atmospheric science staff at the Natural Resources Research Institute (NRRI) at the University of Wyoming began work with the Eden Valley Irrigation District in Farson, Wyoming (Sweetwater and Sublette Counties) to develop an operational glaciogenic seeding program on the southwestern flank of the Wind Rivers. This project was first permitted by the Wyoming State Engineer's Office in 1975 and has been operated each winter since. The authors of this report were told that an operations manual for that program was written by the University staff then involved, but the irrigation district no longer has a copy of that manual. Checks with the Department of Atmospheric Sciences at the University, which grew from the NRRI, failed to find a copy of this manual either. Presently it is considered "lost". Efforts continue to locate a copy.

The present operational program uses three manually operated silver-iodide ice nuclei generators spaced at 10-mile increments along U.S. Highway 191 north of Farson and also two high-altitude remote controlled propane ice crystal generators at higher elevations further to the east. The latter are operated by the Bureau of Reclamation office in Provo, Utah.

2.16   Additional Studies

A number of additional references have also been reviewed. Most were conducted outside Wyoming and so are not included in Task Two but rather where appropriate in Tasks Three, Four, Five and Six. All are included in the comprehensive list of references in Section 16.

3. CLIMATOLOGY OF THE PROJECT AREAS

This section presents a review of the recent climatology of the target areas and, in a larger sense, of Wyoming itself. Focus is, of course, given to the cold season when orographic clouds are most amenable to glaciogenic seeding.

A comprehensive review of Wyoming's climate is provided by Curtis and Grimes (2004). This comprehensive document offers the reader great up-to-date detail on all aspects of Wyoming's climate and was very helpful in this work. Interested readers are referred to the Wyoming Climate Atlas web site at: www.wrds.uwyo.edu/wrds/wsc/climateatlas/.

Wyoming's annual precipitation is highly variable and largely a function of elevation (Figure 3.1).
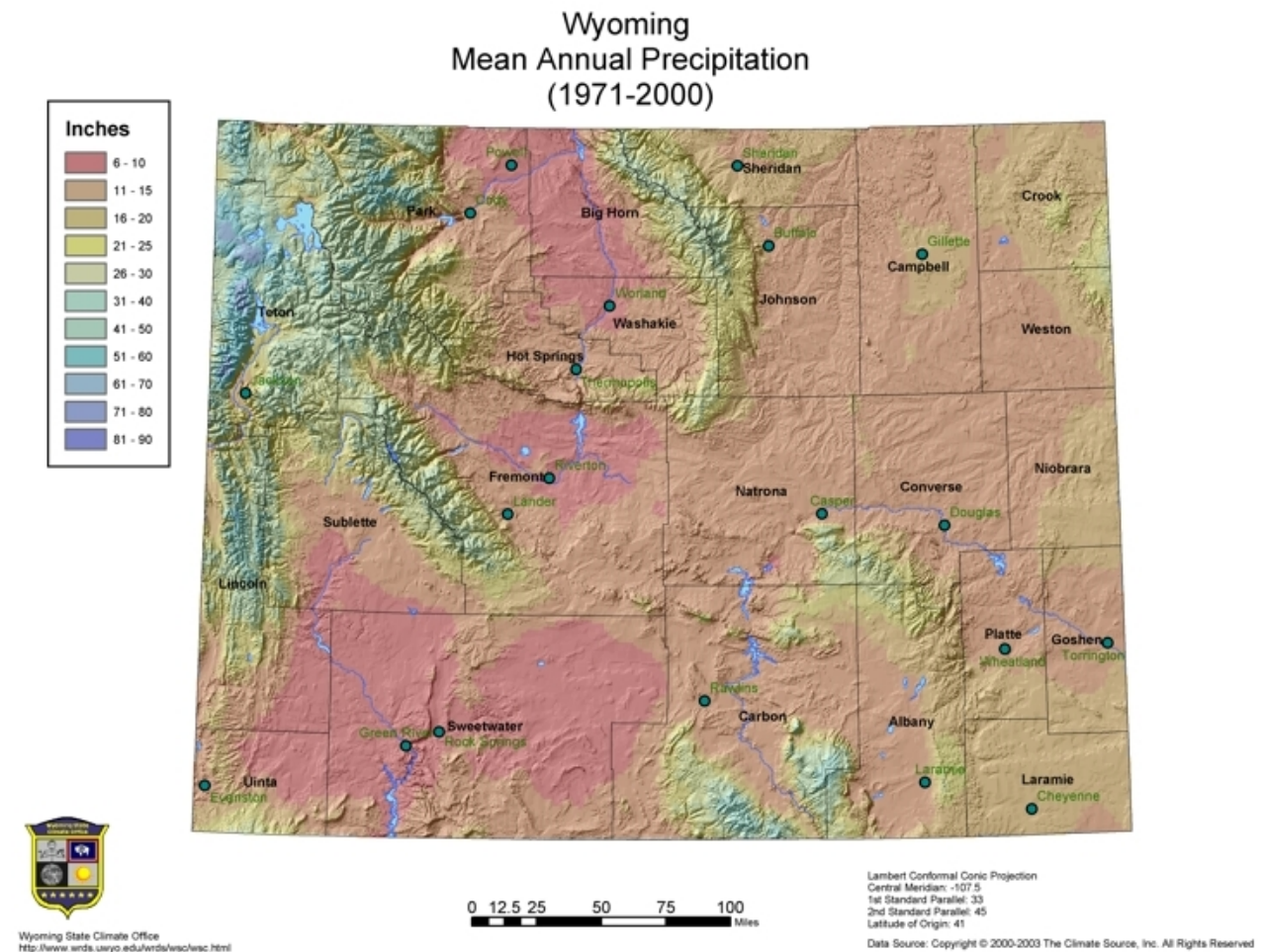
Figure 3.1 - Mean annual precipitation (in inches) is shown for the period from 1971 through 2000, inclusive. Figure from the *Wyoming Climate Atlas*, Curtis and Grimes (2004), used by permission.

Though both of the selected target areas would be expected to receive in excess of ~40 inches of precipitation each year, such has not recently been the case. Prolonged periods of below normal precipitation often give rise in interest in cloud seeding and that situation, at least in part, accounts for the current interest. Dr. Archie Kahan, a former director of the U.S. Bureau of Reclamation's Project Skywater cloud seeding research program, once remarked that "Interest in weather modification is soluble in rain water." Dr. Kahan's remark was essentially correct but cloud seeding or "weather modification" has now developed to the point where it should be considered part of most every water manager's toolbox.

Present technologies to increase precipitation through cloud seeding can supply additional water but only when clouds amenable to seeding are naturally present. In some drought situations, few clouds suitable for cloud seeding operations ever develop and the opportunity to increase precipitation in a meaningful way would be very limited. If applied as a long-term tool, however, seeding operations conducted during normal and near-normal years can significantly increase precipitation, increasing surface and sub-surface soil moisture content, increasing streamflows and helping fill reservoirs. Irrigated crops can be successfully cultivated without mining (pumping) as much groundwater, dry-land farming is more successful and increased water supplies within reservoirs means more water is available for hydropower generation, irrigation and municipal and industrial use. In some cases, additional streamflows improve water quality by diluting previously polluted waters and the situation of threatened and endangered species can also be ameliorated.

In seasons with above-normal precipitation, "seeding suspension criteria" are satisfied relatively early in the season and seeding operations cease (see Section 5 for additional information). Simply stated, when nature provides plentiful water supplies, seeding is not needed nor desired.

The balance of this section discusses specific weather patterns that typically produce precipitation in the Wind River and/or Medicine Bow/Sierra Madre areas and the frequency with which such patterns occur.

3.1   Precipitation and Snow Characteristics

The mean annual precipitation for the period 1971 to 2000 for the State of Wyoming was shown in Figure 3.1. It is clear from that figure that both the Wind River and Medicine Bow Mountain ranges receive anywhere from 25 to 60 inches of precipitation annually, with greater amounts at higher elevations. It is further important to note that approximately 40 to 70% of this precipitation falls in the winter, mostly in the form of snow (Figure 3.2). This is especially evident in the Wind River Mountains where between 60 and 70% of the annual precipitation falls on the highest peaks falls from October through March. These data indicate that a winter cloud seeding program could potentially benefit water resources in these regions because seeding opportunities primarily exist during this time of the year. Both mountain ranges receive more than 250 inches of snow during the winter months (Fig. 3.3).

For any future cloud seeding program, it is also important to determine the frequency of snow and precipitation to determine if sufficient opportunities would exist or if most of the snowfalls are only restricted to a few major events. Figures 3.4 and 3.5 display the average number of days with snowfall totals of more than one inch and snowfall totals of more than five inches, respectively.
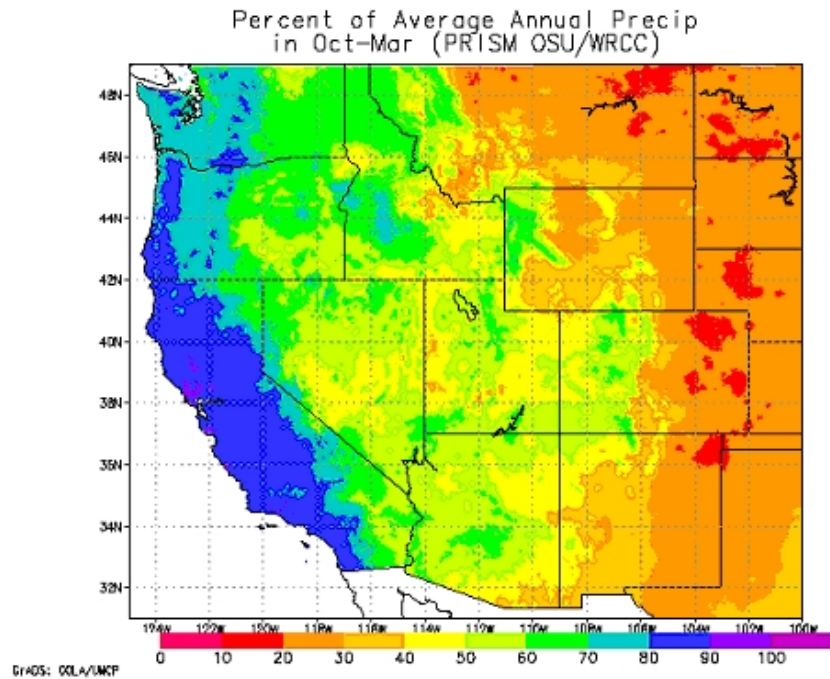
Figure 3.2 - Percentage of annual precipitation that falls between October and March, inclusive. Figure from the *Wyoming Climate Atlas*, Curtis and Grimes (2004), used by permission.
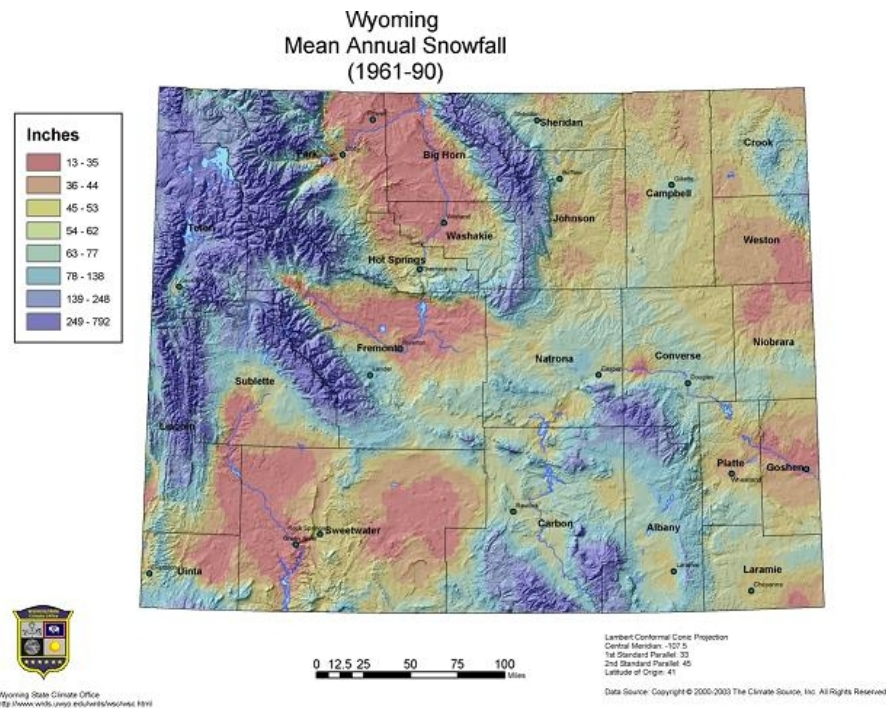
Figure 3.3 - Mean annual snowfall (in inches) is shown for the period from 1961 through 1990, inclusive. Figure from the *Wyoming Climate Atlas*, Curtis and Grimes (2004), used by permission.

While snowfall totals of more than one inch occur on more than 40 days during the winter season at lower elevations, the number of snow days increases to more than 100 days during

the winter season for the higher elevations in both the Wind River and Medicine Bow/Sierra Madre Mountain ranges.
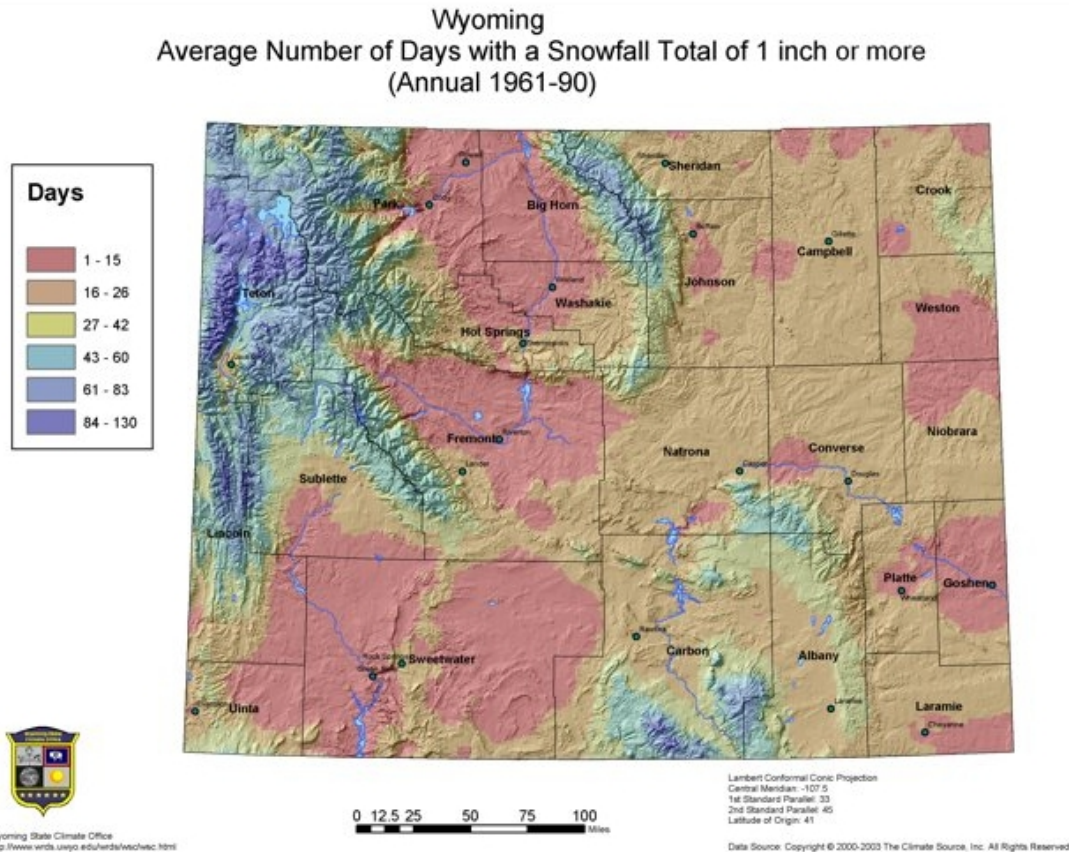
Figure 3.4 - Average number of days with snowfall totals of more than 1 inch for the period 1961 to 1990. Figure from the *Wyoming Climate Atlas*, Curtis and Grimes (2004), used by permission.

Snowfall totals of more than five inches occur on more than 10 days during the winter for the lower elevations and increase to more than 30 days for the highest elevations. These data suggest that seeding opportunities could occur on at least 60 to 80 days during the winter months, which would provide for more than sufficient opportunities to warrant a winter orographic cloud seeding program.

Most of the precipitation and snow during the winter months over Wyoming are associated with extra-tropical low-pressure cold-frontal systems that traverse the region from west to east. These systems are usually associated with snow and precipitation and depending on the proximity, location, movement and strength of these systems, snow and precipitation amounts may differ substantially spatially. The numbers of such systems that have traversed and affected precipitation in the region during the period 1961 to 1998 as a function of month are shown in Figure 3.6.
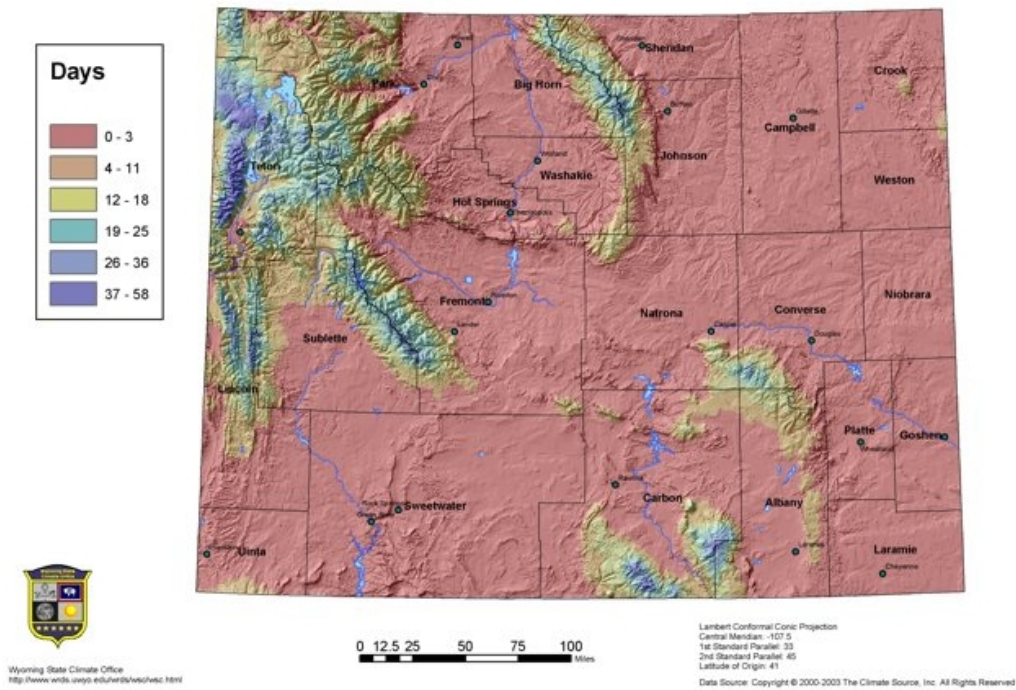
Figure 3.5 - Average number of days with snowfall totals of more than 5 inches for the period 1961 to 1990. Figure from the *Wyoming Climate Atlas*, Curtis and Grimes (2004), used by permission.
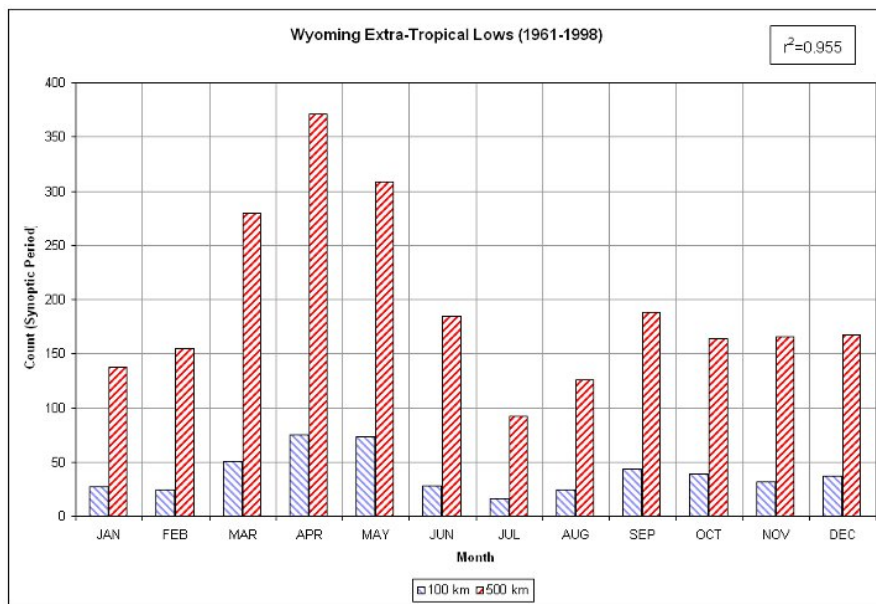
Figure 3.6 - The number of extra-tropical lows within 100km (blue bars) and within 500km (red bars) that traverse the Wyoming region and affect precipitation in the region. Figure from the *Wyoming Climate Atlas*, Curtis and Grimes (2004), used by permission.

It is clear that these systems occur most frequently during the winter months and peak during the spring. However, although the maximum number of these systems tend to occur in April and March, these spring storms do not contribute significantly to the precipitation at higher elevations in the mountains but shows a larger contribution of precipitation along the eastern slopes of the mountain ranges. This is especially evident for the Wind River Mountains where approximately more than 16% of the annual precipitation on the eastern slope of the Wind River Mountains typically falls in the month of April.

3.2 Surface and Hydrologic Characteristics

The maps of topography, land-surface, geological characteristics and top and bottom soil types are shown in Figures 3.7 to 3.9. They are derived from USGS 30-second data. These data were used in the numerical modeling studies described in Section 4. The topography plays an important role determining wind flow patterns around the mountains and associated regions of supercooled liquid water that would be targeted in any winter cloud seeding operations. The two main mountain ranges that will be the focus of this study are the Wind River Mountain range in central western Wyoming and the Medicine Bow/Sierra Madre Ranges in southeastern Wyoming. While the elevation in the Medicine Bow's reach approximately 3000 m MSL, the highest peaks in the Wind River Range reach approximately 3500 m MSL. The orientation of both mountain ranges is approximately in a northwest-southeast direction. The distinct feature of the Medicine Bow/Sierra Madre complex is that it is two ranges of mountains with a high-plateau valley in between. The Wind River Mountain Range is fairly isolated on all sides except the northwestern side where it is surrounded by other mountainous terrain (Figure 3.7).
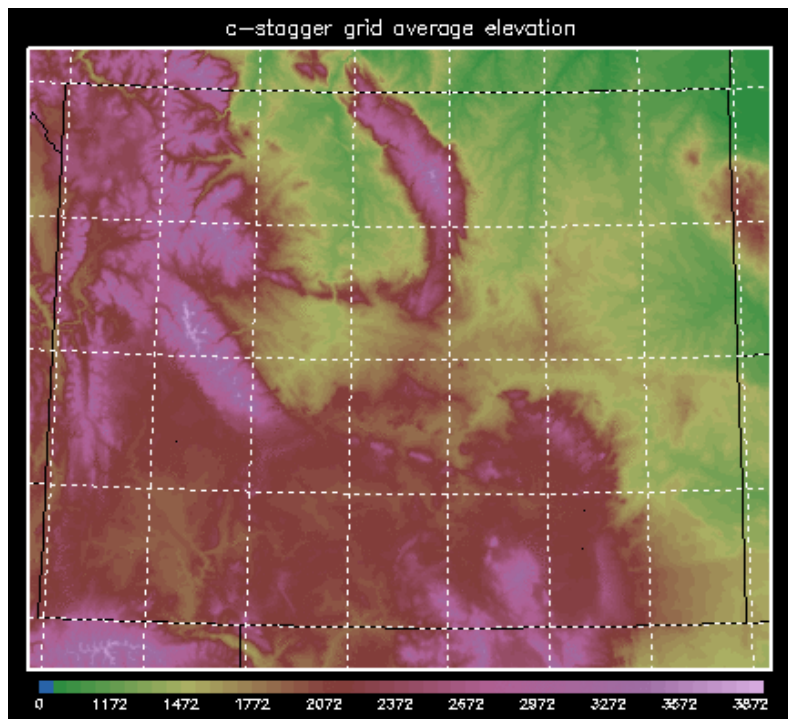
Figure 3.7 - Topographical map of Wyoming showing the different mountain ranges. The elevation ranges from about 1000 m MSL in the northeast to more than 3500 m MSL in the western parts of the State including the Wind River Mountain range. (Source: USGS 30-second topography data.)

The location, orientation, steepness of the slopes, height and surrounding topography are all important determining wind flow and associated patterns of supercooled liquid water either near the surface associated with upslope flow or aloft in the atmosphere associated with topographically induced gravity waves (Bruintjes et al. 1994). These features in turn will determine temporal and spatial precipitation patterns as will become evident in the next section.
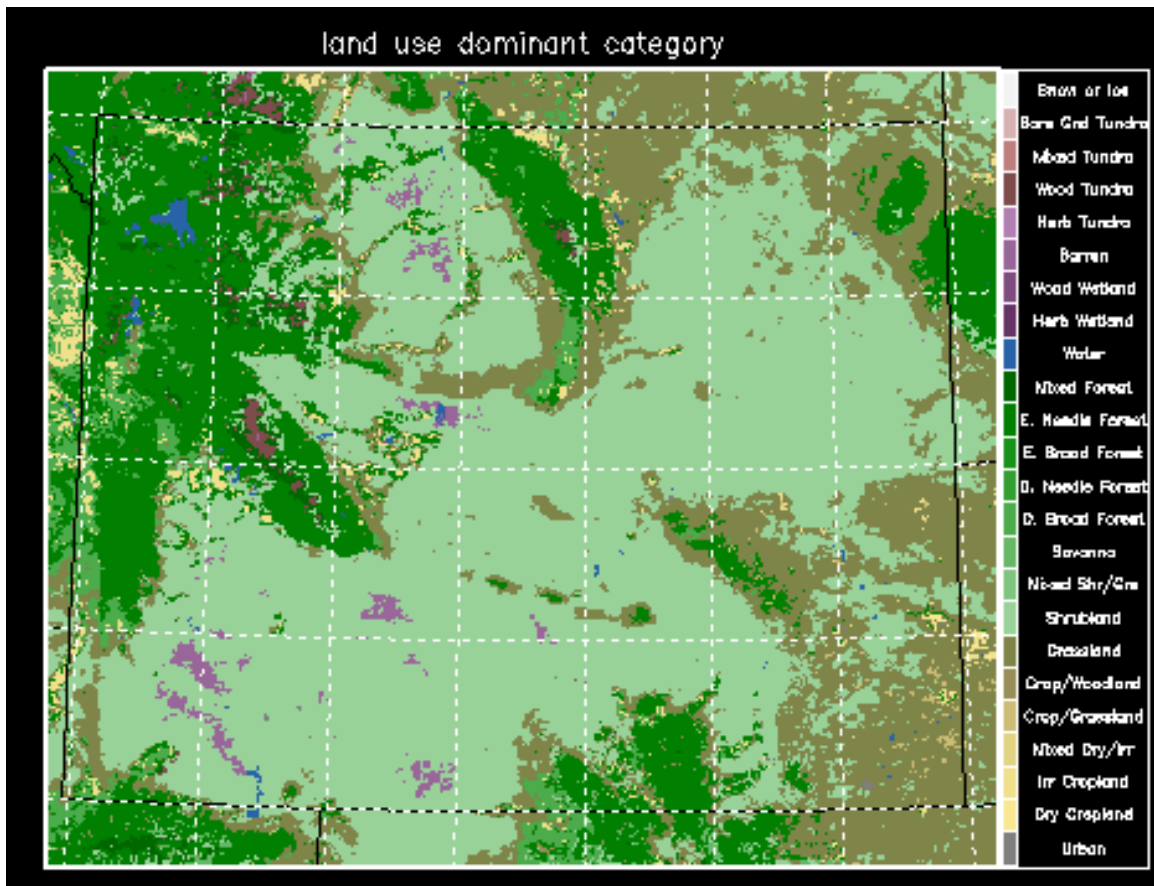
Figure 3.8 - Wyoming land-surface cover and characteristics. A legend is provided at the right portion of the figure. (Source: USGS 30 second land surface cover data.)

While most of the state is covered in shrub land grasses, the mountains are mostly forested with even some wood tundra along the highest peaks of the Wind River Mountain Range (Figure 3.8). The dominant top-layer soil type is shown in Figure 3.9. The soil types are mostly of a sandy loam and clay types except for some of the higher elevation in the mountains in the northern and northwestern parts of the states where even in some places glaciers are present.

The Wind River Range is an unbroken 100-mile long barrier in west central Wyoming that is host to 63 glaciers covering 17 square miles in area. Seven of the 10 largest glaciers in the American Rocky Mountains are found in the Wind River Range with areas from 393 to 1130 acres (Bonney 1987), while the total area of glaciers in the Wind River Range is larger than that of all other glaciers (a total of 134 covering 12 square miles) in the American Rockies (Field 1975, Davis 1988).

Glaciers contribute an undocumented amount to streamflow in Wyoming. Glaciers can be considered as natural reservoirs that store water in the winter and release it in the summer. Glacier runoff is likely to be most important during the late summer and early fall when low flows are critical for consumptive water users and in streamflow needs. In addition, glaciers may release larger proportions of the water flow in years of low precipitation when water from other sources such as winter snowpack may be in short supply.

According to most authors (e.g., Meier 1951, Dyson 1952, and Mears 1972) glaciers in the Wind River Range have generally been in a negative regime (decline) since 1850. While the most pronounced retreat occurred in the late 1930s, the glaciers continued to retreat, some at an alarming rate. Dyson (1952) reported that glaciers in the Wind River Range were retreating at a rate of 7 to 41% per year. Systematic studies of glacier mass balance have not been conducted on Wind River glaciers since the one- or two-year studies in the 1950s. The contribution of runoff form glaciers to the total snowmelt runoff should not be discounted, and could also potentially be impacted by a cloud seeding program. Enhancement of snowpack over the glacier regions may also benefit future runoff from glaciers.
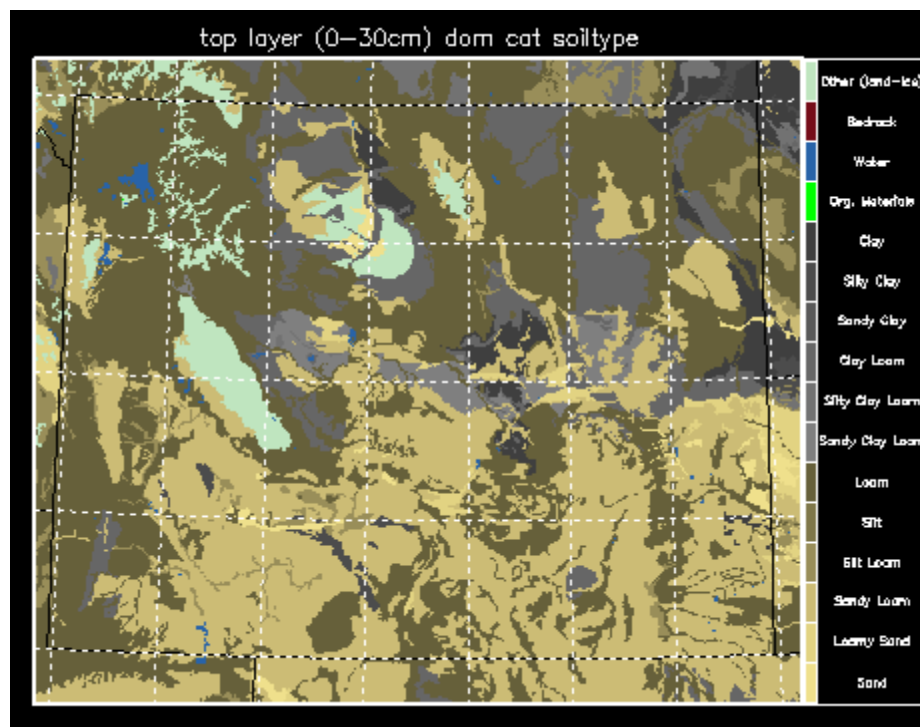
Figure 3.9 - Topsoil types in the State of Wyoming. A legend is provided in the right-hand portion of the figure. (Source: USGS 30 second topsoil data)

Annually snowmelt runoff forms the largest contribution to water resources in the region with major rivers originating from both the Medicine Bow and Wind River Mountain ranges. However, estimating and modeling the amount of runoff and the relationship between snowpack and runoff still remains an active area of research.

Both conceptual and physical approaches have been employed in snowmelt runoff modeling. Conceptual models propose a mathematical relationship between snowmelt and measured quantities; thus, melt can be calculated without treating in detail all of the physical processes

and parameters that affect snowmelt. Conceptual models have the benefit of requiring less informational input but suffer from the uncertainty that parameters estimated under one set of model conditions are or are not applicable to other conditions. Though non-linear relations may improve the prediction of seasonal snowmelt volume versus that from linear models, their use is limited by the failure of transformed data to satisfy the condition of nonlinearity (Dey et al. 1992). Conceptual models based on temperature index methods have been used to illustrate the sensitivity of snow-covered basins to climate change and such efforts will improve with the development of models that more directly incorporate radiative exchange into the calculation.

One of the main obstacles to physically-based modeling is the accumulation of the necessary meteorological and snow-cover data to run, calibrate, and validate such models. For example, basin discharge has frequently been used as the sole physical criterion of model calibration and performance assessment for conceptual snowmelt models. But as it is an integrated response to melt and runoff, basin discharge is not sufficient to discriminate between the effects of the multiplicity of data inputs driving physical models and that distributed snow cover data are required to assess model performance.

3.3   SNOTEL Data

One of the most useful sources of wintertime precipitation data is the network of "SNOTEL" sites throughout the American west. These site telemeter snowfall data (hence "SNOTEL") in near real-time providing a detailed, time-resolved record of wintertime precipitation events. The network is operated and maintained by the U.S. Department of Agriculture's (USDA's) Natural Resource Conservation Service (NRCS). Access to current and historical SNOTEL data is available via the Internet at http://www.wcc.nrcs.usda.gov/snotel/Wyoming/wyoming.html. Data for the last five years has been examined for a number of the sites within the project target areas (Figure 3.10).

A consistent picture emerges: water (snowpack) accumulates at a more or less linear rate up until the spring thaw, at which time the water melts and the spring runoff begins. If the weather is excessively warm, the spring melt is rapid and the runoff may be brief but characterized by large flows. Little soil moisture recharge may occur. Conversely, if the weather is cool, the runoff occurs over a longer period and at a lower rate and greater soil moisture recharge will likely occur.

Thus, if the weather is warm and the runoff occurs rapidly, reservoirs may fill too quickly and "excess" water may have to be spilled to retain flood control capability. When the runoff occurs more slowly, less peak flow is spilled from the reservoir, providing a greater percentage for storage and ultimately hydropower production.

Of the stations examined in some detail, Cold Springs, Elkhart Park and Deer Park were examined for the Wind Rivers and Battle Mountain for the Medicine Bow/Sierra Madre Ranges.
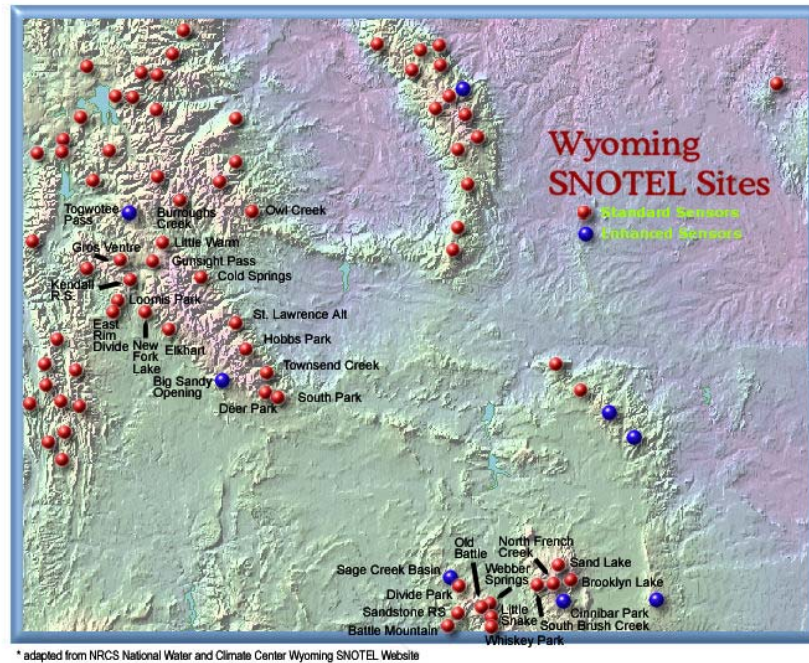
Figure 3.10 - The locations of the Wyoming SNOTEL sites are shown. Sites examined in some detail in this study are labeled by name. (Source: NRCS.)

3.3.1   Wind River Range

<u>Cold Springs SNOTEL Data</u>
The most recent five water years' data were examined for each of the stations. The seasonal plot of the Cold Springs SNOTEL site snow water equivalent is shown in Figure 3.11 below.
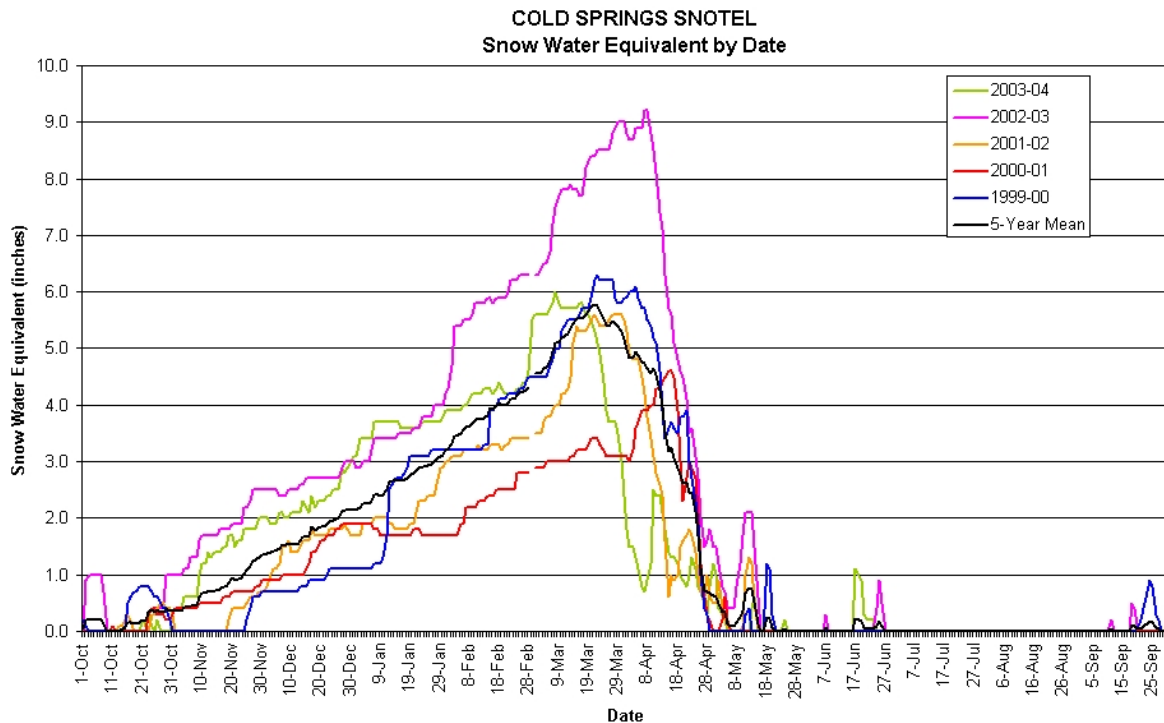
Figure 3.11 - Snow water equivalent measured by date for each of the five most recent snow water years. The five-year mean value is shown in black. (Data source: NRCS.)

To assess the wind directions associated with the snowfall, a second plot was made comparing upper air winds at 700 mb and 500 mb as measured by the Riverton, Wyoming 1200 UTC sounding with the total precipitation observed on the balance of the calendar day (Figure 3.12). The primary precipitation mode appears to be when winds (700 mb and 500 mb) are westerly across the barrier. This is as expected. The period from 1 October 2003 through 30 April 2004 is plotted in Figure 3.12 to eliminate as many convective events as possible. However, the 1.3 inch precipitation event associated with northeast winds at 700 mb was convective in late April. It is worth noting that northeast flow is also upslope for the Wind River Range.

A large fraction of all events occurred when winds were westerly. The weaker secondary maximum associated with easterly flow would also be upslope. The wind corridor described by Martner and Marwitz (1982) significantly impacts travel on I-80 because visibility due to blowing snow during winter and wind loading on high-profile vehicles year-around. The Wyoming Department of Transportation informally has expressed concern that cloud seeding should not exacerbate the situation.
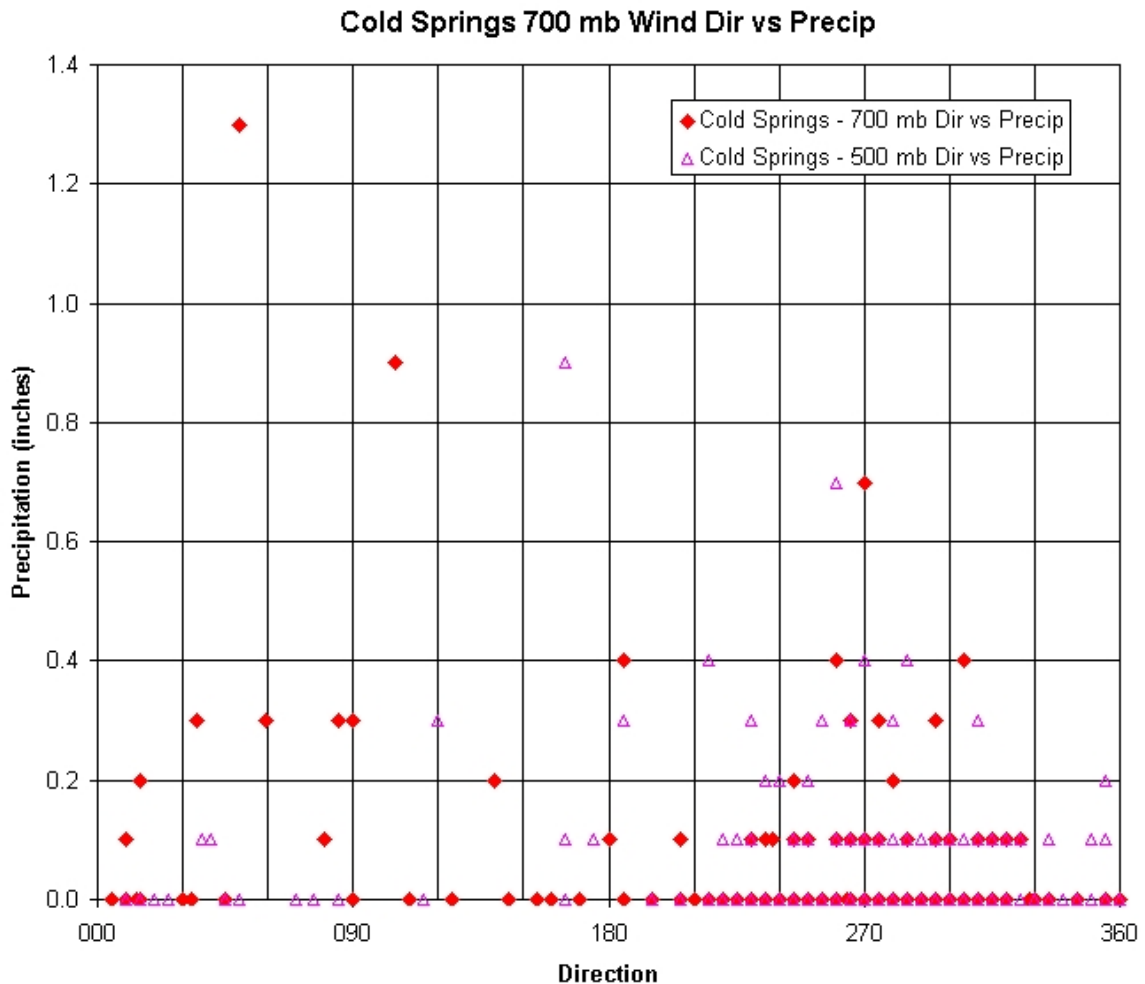
Figure 3.12 - SNOTEL precipitation observed at the Cold Springs site in the Wind River Mountains is shown as functions of 700 mb (approx. 10,000 ft MSL) and 500 mb wind directions (approx. 18,000 ft MSL). (SNOTEL data courtesy of NRCS, upper air wind data courtesy of NWS.)

Elkhart Park SNOTEL Data
The seasonal plot of the Elkhart Park SNOTEL site snow water equivalent is shown in Figure 3.13. The Elkhart Part site is located on the western slope of the Wind Rivers (see again Figure 3.10) with a lengthy fetch across the Green River Basin. The seasonal totals are greater than those observed at Cold Spring but the trends are very much the same.

A plot analogous to Figure 3.12 was also generated for Elkhart Park (Figure 3.14). The story is the same in this case also-as expected, precipitation occurs when moist cross-barrier flow exists.
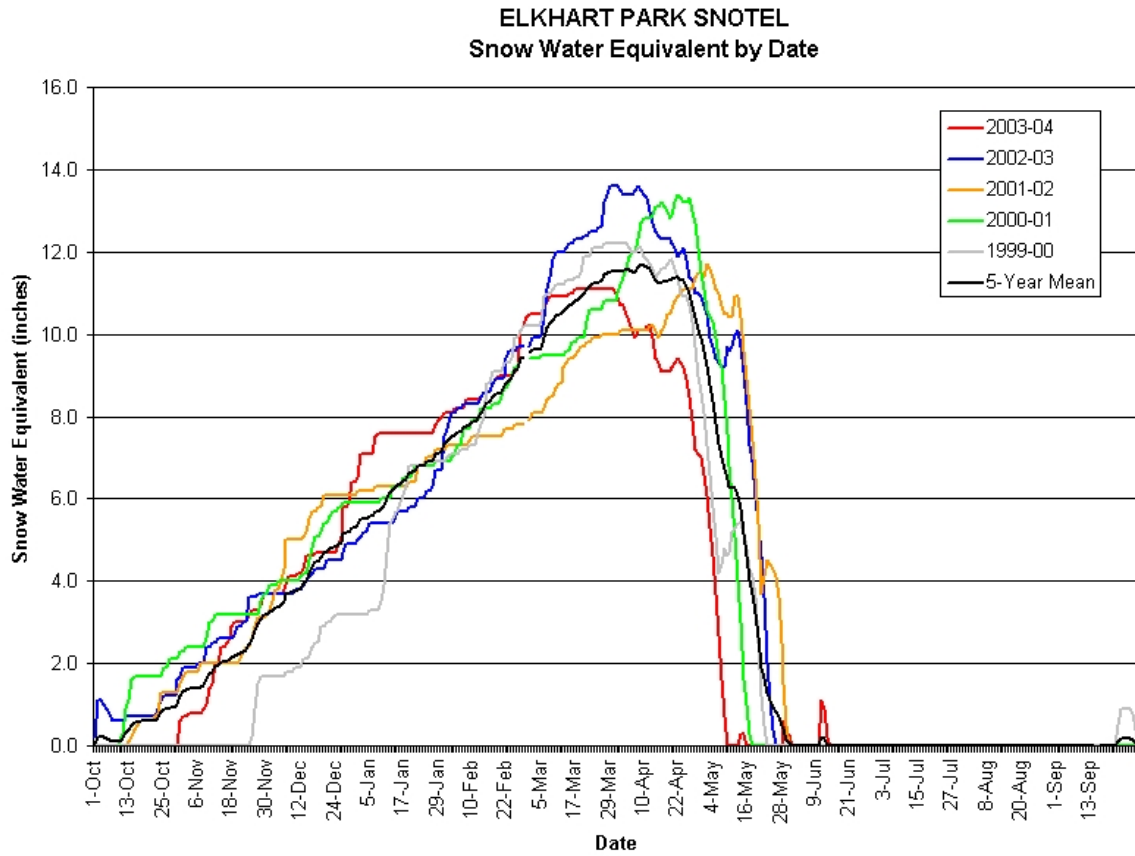
Figure 3.13 - Snow water equivalent measured at the Elkhart Park SNOTEL site by date for each of the five most recent snow water years. The five-year mean value is shown in black. (Data source: NRCS.)
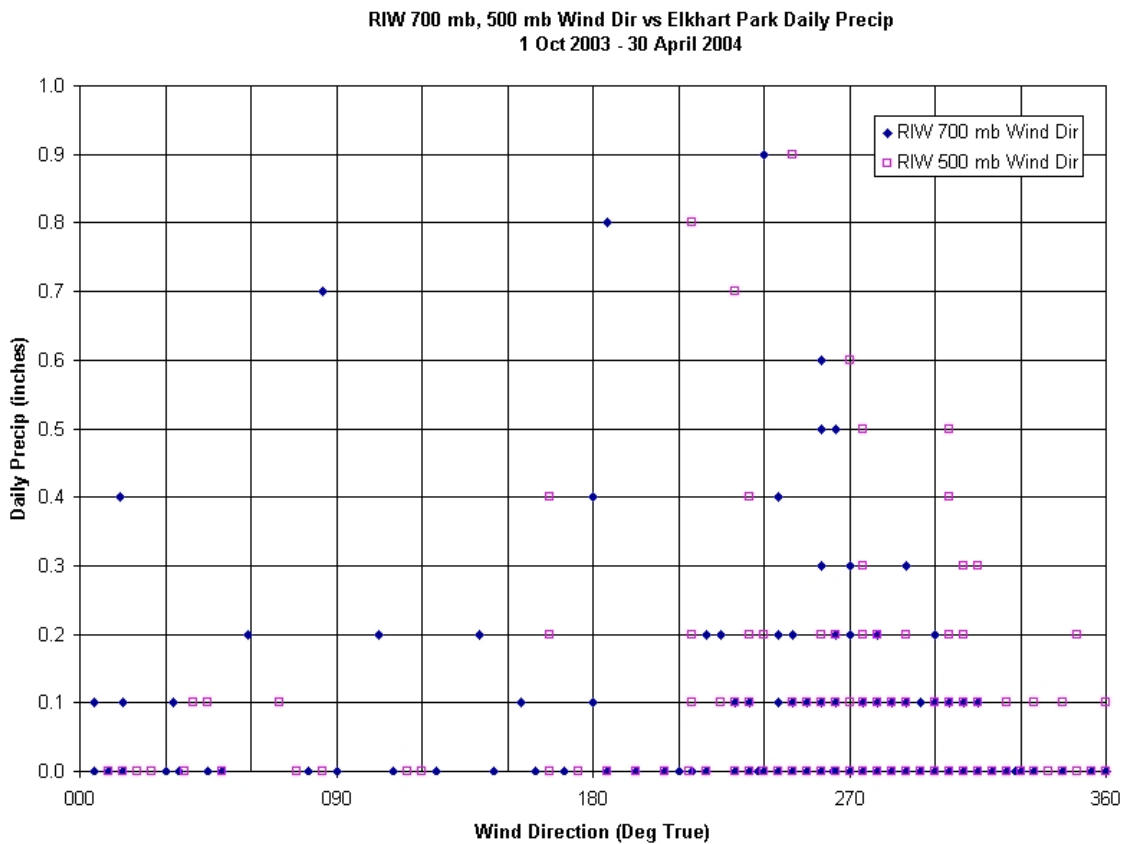
Figure 3.14 - Precipitation measured from 1 October 2003 through 30 April 2004 as functions of 700 mb and 500 mb wind speed, as measured by the nearby National Weather Service sounding released daily at 1200 UTC from Riverton, Wyoming. The story is essentially the same as that told by Figure 3.12: the precipitation occurs when cross-barrier flow is present. (SNOTEL data courtesy of NRCS, upper air wind data courtesy of NWS.)

Additional analogous plots were made for the Deer Park SNOTEL site with similar findings. Deer Park is located on the south end of the Wind Rivers and so (we thought) might exhibit a somewhat different response, especially as related to wind direction. These two graphics are shown as Figures 3.15 and 3.16.
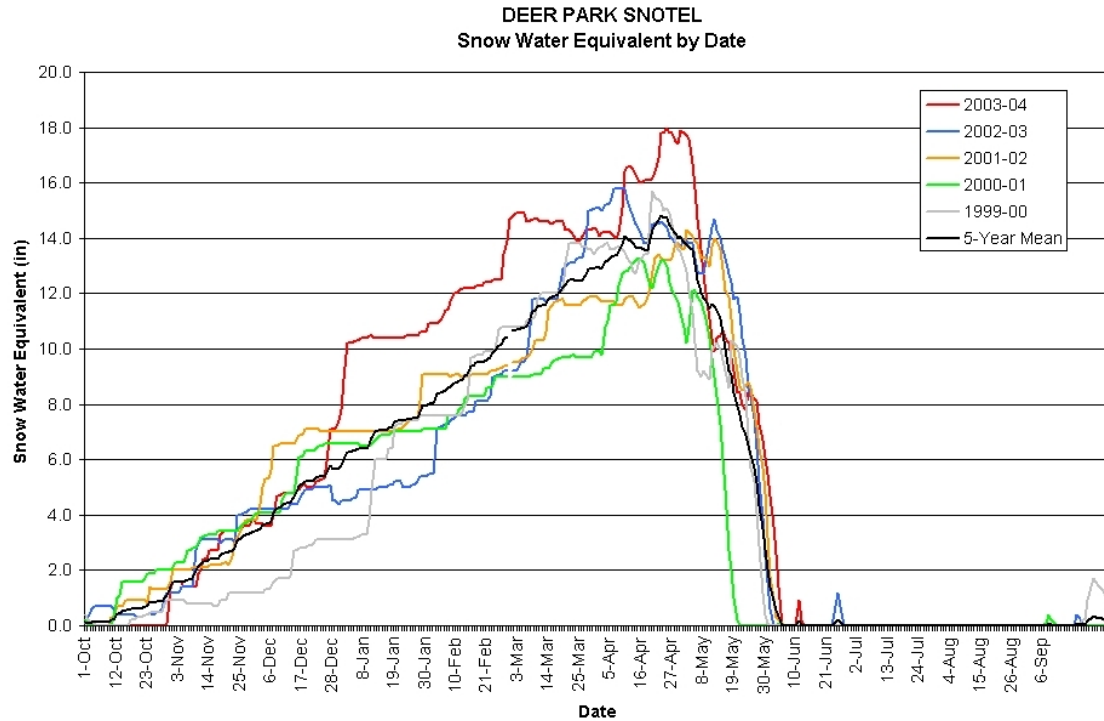
Figure 3.15 - Deer Park SNOTEL snow water equivalents measured at midnight local time for the most recent five water years. The five-year mean is shown in black. (Source: NRCS.)
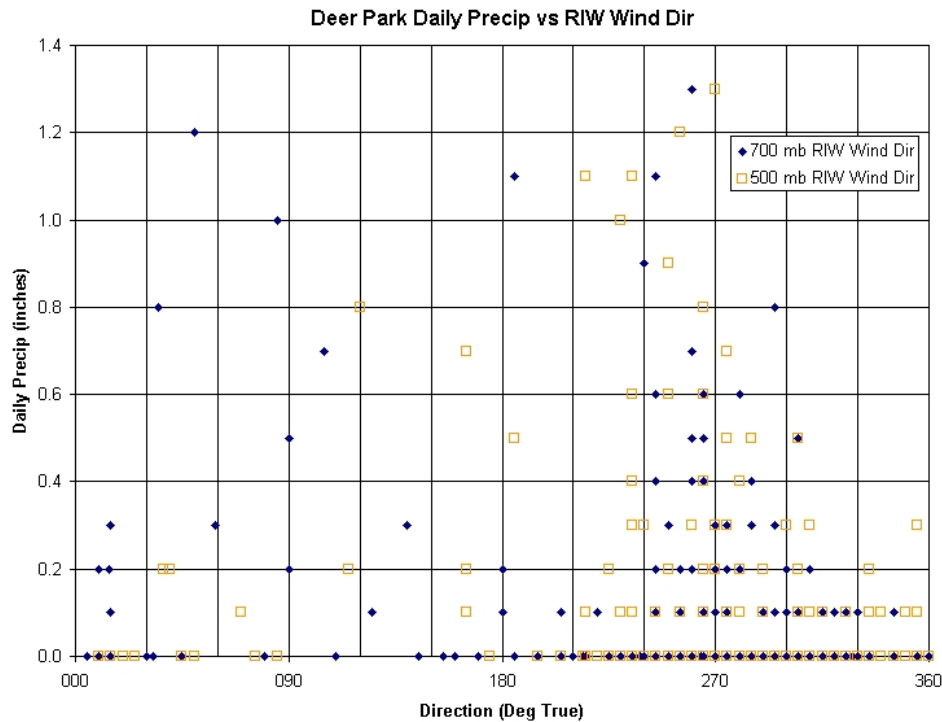
Figure 3.16 - Precipitation observed at the Deer Park SNOTEL site as a function of wind direction. The dependence on westerly flow is even stronger in this case. (SNOTEL data courtesy of NRCS, upper air wind data courtesy of NWS.)

3.3.2   *Medicine Bow – Sierra Madre Ranges*

To gain some sense of how wind flow relates to precipitation in the Medicine Bow/Sierra Madre Mountains, data from the Battle Mountain SNOTEL site were examined again in conjunction with the NWS upper air data from Riverton.

The Battle Mountain SNOTEL snow water equivalent (SWE) plot for the last five water years (Figure 3.17) shows trends very similar to those site examined in the Wind River Mountains: a gradual increase beginning in late fall and through the winter, coupled with a fairly rapid decrease as the spring runoff occurred.
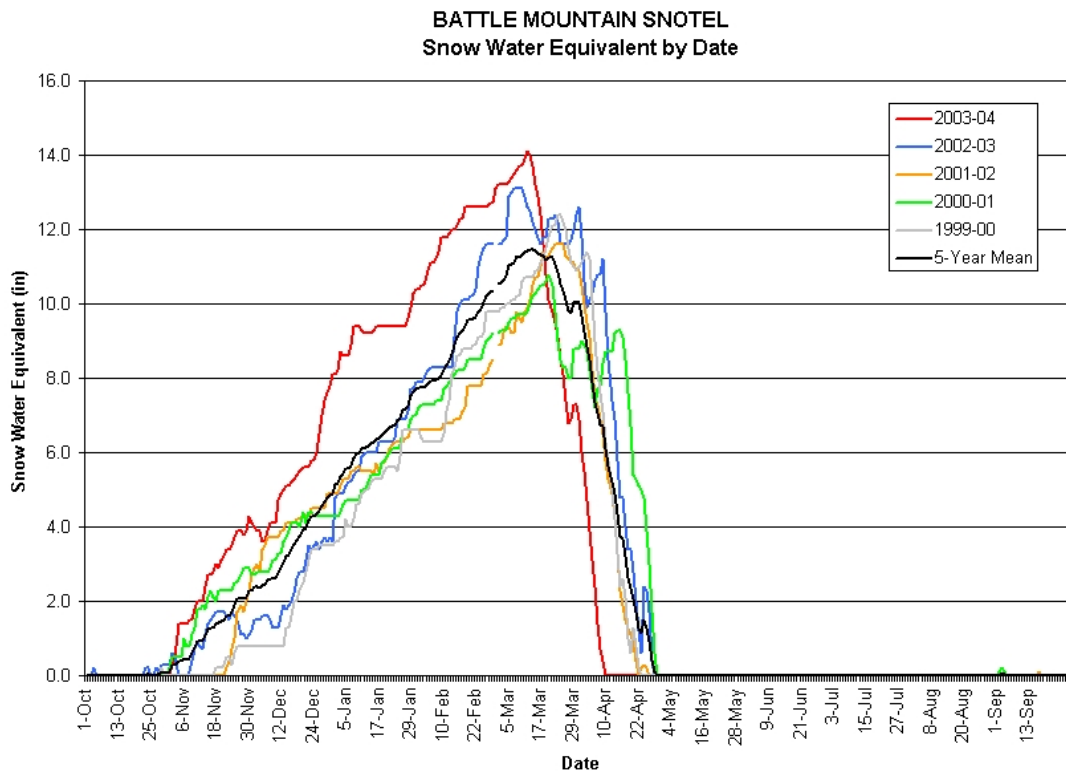
Figure 3.17 - Battle Mountain SNOTEL site snow water equivalent in the Sierra Madre Mountains. The five-year mean is shown in black. Trend and character are indistinguishable from the analogous Wind River plots. (Data source: NRCS.)
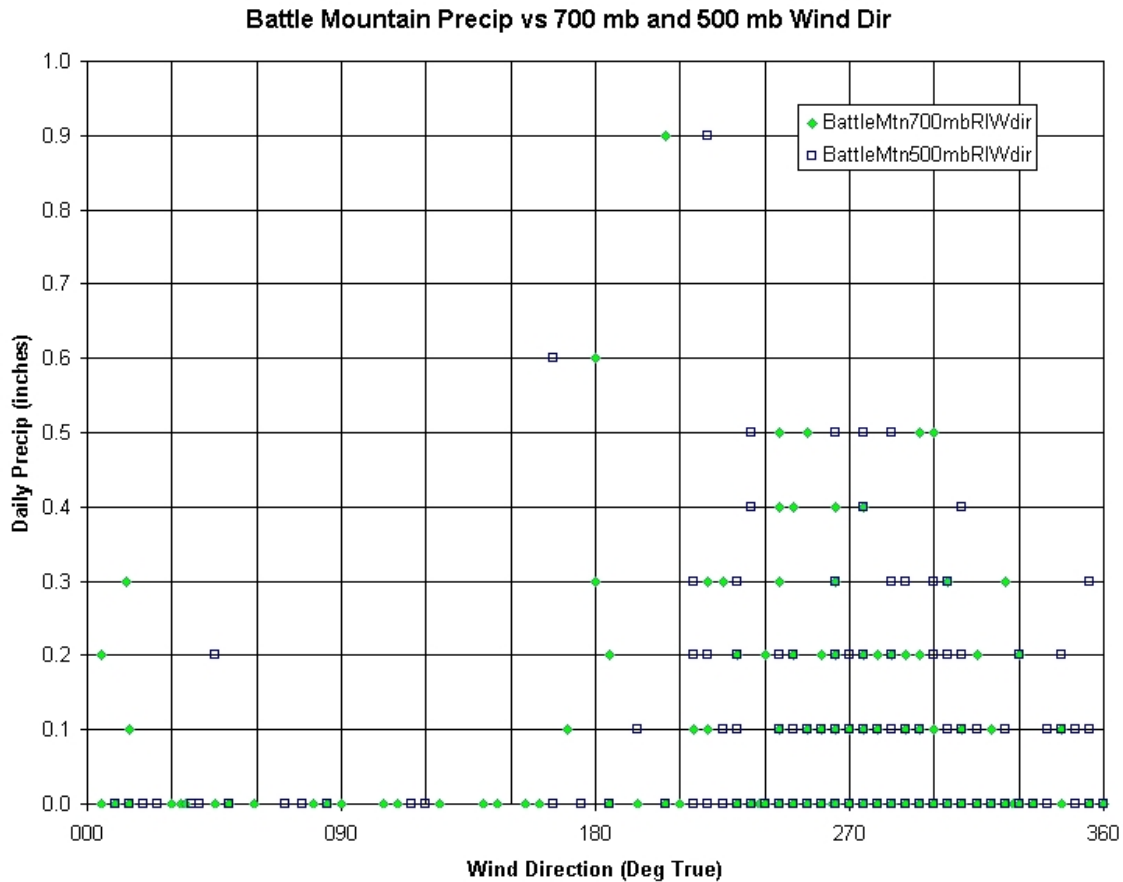
Figure 3.18 - Battle Mountain SNOTEL site precipitation for 2003-04 as a function of 700 mb (~10,000 ft) and 500 mb (~18,000 ft) wind directions as measured by the Riverton NWS 1200 UTC soundings. Several additional SNOTEL sites in the Wind Rivers and Medicine Bow – Sierra Madre Ranges were also examined with very similar findings. (SNOTEL data courtesy of NRCS, upper air wind data courtesy of NWS.)

The primary conclusion is that precipitation in both ranges occurs primarily when wind direction at 700 mb (near or a little below crest elevation) and at 500 mb (well above crest elevation) is westerly. This dependence is evident at all sites but weakest at the more northern sites located on the western side of the Wind River Range.

Temperatures are often too warm for silver iodide seeding early in the fall (October), but by November this is most often not an issue. Convective storms, or convection embedded within the orographic clouds, are most common in spring (April).

Though the climatology suggests that a seeding program would be most effective from November or mid-November on into the winter, it is very important to note that equipment must be installed and tested well before. It is recommended that plans be made to install all remotely sited equipment by 1 October.

4. DEVELOPMENT OF PRELIMINARY PROJECT DESIGN

4.1 General Background

Precipitation enhancement from mixed-phase clouds (i.e., clouds or parts of the clouds with temperatures below 0°C) has been the focus of most weather modification research and operations around the world. The microphysics and dynamics of these cloud systems is complex and, especially in the case of convective storms, are characterized by large natural variability. Establishing cause-and-effect relationships through the complete chain of events leading to precipitation formation is extremely challenging. Glaciogenic seeding material is the most common seeding material used for precipitation enhancement. Hygroscopic seeding material, such as salt powders, also has been used but its early applications generally proved to be less effective than glaciogenic seeding material. During the past decade, however, tests have been conducted on mixed-phase convective clouds using small (sub-micron to tens of microns in diameter) hygroscopic particles released by pyrotechnic flares with somewhat different results. The results of glaciogenic and hygroscopic precipitation enhancement techniques are distilled in the following section (see Box 2.1 of National Research Council Report (NRC 2003) for a summary).

Based on the quantity of glaciogenic seeding material used to enhance ice content, two seeding concepts have historically been proposed and widely referred to as "static" and "dynamic" seeding. In the static seeding concept the aim is to capitalize on the less-than-optimal ice crystal concentrations often present in nature that lead to prolonged periods of supercooled liquid water (SLW), especially in orographic clouds. These regions of supercooled water have to exist for a sufficient length of time for ice crystal growth and precipitation to occur. In the dynamic seeding concept the emphasis is on the release of latent heat by rapid freezing, which enhances buoyancy and invigorates cloud growth, thereby increasing precipitation production. It should be noted that these concepts are not mutually exclusive because they both result in increased ice crystal concentrations and affect cloud dynamics. The same seeding material is used in both seeding concepts; only the quantity of seeding material is varied. While the dynamic seeding concept primarily applies to convective clouds, the static seeding concept has been widely utilized in orographic and layer-type clouds, as well as in convective clouds.

Table 4.1 - Examples of Static Glaciogenic Winter Orographic Cloud Seeding Experiments in Precipitation Enhancement

Type of cloud	Experiment	Reference
Winter orographic clouds	Lake Almanor experiment	Mooney and Lunn 1969
	Sierra Cooperative Pilot Project (SCPP)	Reynolds and Dennis 1986, Deshler et al. 1990
	Climax I and II	Grant and Mielke 1967, Mielke et al. 1981
	Bridger Range experiment	Super and Heimbach 1983, Super 1986
	Tasmanian experiments	Ryan and King 1997
	Puglia experiment	List et al. 1999

In the case of static seeding of winter orographic clouds (Table 4.1), important results include:

- Recognition of the complex interactions between terrain and wind flow in determining regions of cloud liquid water and, later, through microwave radiometer measurements, the existence of a layer of SLW;
- Acknowledgment of the need to target and track the dispersion of seeding material and the demonstration that complex flows including ridge-parallel flows below the ridge crest exist in pronounced terrain;
- Evidence of marked increases in ice particle concentrations leading to increased precipitation depending upon the availability of supercooled liquid water;
- Re-emphasis of the need for physical data that can be used together with numerical models to identify the spatial and temporal changes in cloud structure;
- Development of highly efficient silver chloro-iodide ice nuclei and other fast acting, highly efficient ice nucleating pyrotechnic and generator devices; and
- Application of methods to detect traces of seeding agents in snowpack and rain water.

A review of the relevant literature immediately highlights the correlation between the temporal and spatial evolution of cloud liquid water (CLW) and the complexity of the terrain in winter orographic systems (Rauber et al. 1986, Rauber and Grant 1986, Marwitz 1986, Deshler et al. 1990, and Huggins and Sassen 1990). Rangno (1986) notes that the cloud variability encountered in several mountainous areas in the United States poses severe challenges for forecasting seeding opportunities and determining a treatment strategy, especially when seeding opportunities are short-lived. This conclusion was re-iterated by Super and Holroyd (1989) based on studies in Arizona where they specifically noted that, although CLW was present in all storm systems, it was highly variable in time. However, in most of these studies, measurements of CLW with microwave radiometers indicated many hours when CLW existed and could potentially be seeded (Huggins 1995).

Over mountainous terrain and in frontal systems the timely identification of regions of SLW and the efficient targeting and dispersing of seeding material remain difficult problems. These clouds are part of major winter cyclonic storms, which often have continuously changing wind flow regimes and cloud structures. Major uncertainties include the identification of the right cloud at the right time, the response time for delivering seeding material, the coverage of releases, and the potential for cloud-volume filling. Evidence from plume tracking and measurement of seeding chemicals in fallen snow shows that plumes of seeding material often do not fill and catalyze the intended cloud volume (Reynolds 1988, Stone and Warburton 1989). Experiments to seed wintertime orographic and frontal clouds for precipitation enhancement (snowpack and rainfall augmentation) have highlighted the complex interaction between the terrain and the wind-flow structure in targeting and dispersing seeding material. This interaction explains the difficulty experienced in showing cause and effect through seeding experiments over the Sierra Nevada (Deshler et al. 1990).

Marwitz (1986) compared cloud and precipitation evolution in winter frontal orographic clouds over the Sierra Nevada and San Juan mountains and found significant differences in flow dynamics and microphysical processes between the two mountain ranges. These included differences in the strength of the low-level barrier jet and associated low-level moisture transport during periods of stable flow and the development of different local circulations during unstable flow. Comparison of storms in the Sierra Nevada to those in the San Juans showed colder cloud bases and tops along with higher CCN and cloud droplet concentrations in the San Juans. As a result, broader cloud droplet size distributions were observed in the Sierra Nevada clouds with a secondary ice multiplication process (Hallet and Mossop 1974) that was not observed in

storms over the San Juan Mountains. In addition, riming growth appeared more important in the warmer cloud systems. More recent studies in the Tushar Mountains in Utah (Long et al. 1990, Sassen et al. 1990) and the Mogollon Rim area of Arizona (Klimowski et al. 1998, Bruintjes et al. 1994) illustrated changes in the character of storm dynamics and microphysics with stability, and the interactions between orographic cloud structures and mesoscale precipitation bands. In the Arizona case an active "seeder/feeder" cloud system was evident. The clouds in Wyoming (see Section 2) should be more similar to the clouds in the San Juans and the Bridger Range in Montana.

Klimowski et al. (1998) and Philippin and Betterton (1997) also showed that there was a high variability of CCN concentrations. Concentrations were clearly larger during times of convective activity and unstable air masses when the influence of surface sources was enhanced. During stably stratified flows, CCN concentrations were substantially lower and decreased strongly with altitude resulting in lower concentrations of CCN and droplets in regions of cloud associated with gravity wave updrafts. This was also substantiated by differences in cloud droplet concentrations. These differences again affected the microphysical processes of precipitation development.

Changes in the concentrations of precipitating ice crystals, ice nuclei, and precipitation rate have been observed after seeding in frontal and topographically forced regions. In some experiments seeding has produced strong evidence of precipitation increases, including the Tasmanian experiments when cloud top temperatures were between $-10^{o}C$ and $-12^{o}C$ in south-westerly airflow (Ryan and King 1997). Additionally, results from the Bridger Range experiment showed an order of magnitude increase in ice particle concentration—contingent upon available SLW—leading to increased precipitation. In such experiments the biggest challenge, again, was to collect sufficient physical data on the links in the chain of events to support statistical results.

The results from the CLIMAX I and CLIMAX II experiments (Grant and Mielke 1967, Mielke et al. 1981) provided compelling evidence in the United States for enhancing precipitation in wintertime frontal orographic clouds. However, the results were challenged by Rangno and Hobbs (1987, 1993). The Rangno and Hobbs reanalyses indicate a possible increase in precipitation of about 10 percent, which is less than originally reported, but it still is a significant amount. Cotton and Pielke (1995) noted that the design, implementation, and analysis of this experiment were clearly a learning process, not only for meteorologists but also for statisticians. Many of the cloud systems in orographic snowpack enhancement programs were not simply "blanket-type" orographic clouds, but most often they were part of major winter cyclonic storms with continuously changing wind-flow regimes and cloud structures, including both temporal- and spatial-changing CLW regions (Rauber et al. 1986, Rauber and Grant 1986).

Precipitation formation mechanisms can differ dramatically from one location to another, and even within a single location, depending on the meteorological setting. Precipitation growth can either take place through coalescence or the ice process or a combination of the two. In clouds with tops warmer than $0^{o}C$, precipitation develops by means of the coalescence process. However, when cloud tops reach temperatures colder than $0^{o}C$ ice can develop. Precipitation can then develop via either the coalescence--freezing mechanism (CRG) (Braham 1986), ice crystal growth by vapor diffusion followed by riming growth into graupel (IRG) mechanism (Silverman, 1986), ice crystals aggregating into precipitation particles (Heymsfield 1986, Prasad et al. 1989), or a combination of two or more of these mechanisms. The numbers and sizes (spectrum) of cloud droplets can also vary dramatically, depending on the CCN size distribution.

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A maritime droplet spectrum will consist of fewer particles but more larger drops than a continental spectrum (Pruppacher and Klett 1978). In addition, ice crystal concentrations can also vary greatly, depending on temperature and whether an ice multiplication process is active.

Depending on the temperature at which crystals originate, ice crystals develop with different shapes which in turn have different riming and aggregation characteristics depending on the size of the cloud droplets that influence the precipitation formation mechanism. Bruintjes et al. (1987) showed that ice crystals nucleated between the -5 and -10°C level rime more quickly and develop into graupel particles faster than ice crystals nucleated at other temperature levels, assuming a sufficient amount of supercooled water is available. Recent evidence suggests that the type of hygroscopic chemicals within a drop or ice crystal and electrical effects both within particles and in the cloud have significant impacts on the development of precipitation (Schlamp et al. 1976, Finnegan and Pitter 1988, Pitter and Finnegan 1990). These are further complications to conceptual models of seeding effects.

Aggregates of ice particles are also found to act as precipitation embryos (Vali 1985, Heymsfield 1982). Hobbs (1974) showed that the probability of finding aggregates in a cloud increases with increasing temperature and particle concentration. Heymsfield (1986) in a modeling study concluded that aggregation appears to be an important growth mechanism at temperatures where crystals grow rapidly along one crystal axis (-5 and -15°C regions), based on results obtained in the High Plains Experiment (HIPLEX). The physical mechanism of crystal aggregation is not yet fully understood. It is therefore difficult to model aggregation, and many simplifying and potentially unrealistic assumptions have to be made when modeling this process. Aggregation might prove to be an important mechanism in cloud seeding experiments to enhance rainfall.

Mesoscale numerical models, sophisticated radars, microwave radiometers, and tracer studies could help substantially in identifying the spatial and temporal changes in cloud structures and associated seeding potential (Bruintjes et al. 1994, 1995, Huggins 1995, Klimowski et al. 1998, Reinking et al. 1999). Focused numerical modelling studies on the questions raised by targeting supercooled or liquid water in mountainous terrain can advance the understanding of seeding effects (Orville 1996). Studies by Bruintjes et al. (1994, 1995), Heimbach and Hall (1994, 1996) have shown the utility of using state-of-the-art models for guiding and understanding the flow patterns and associated CLW regions in complex terrain.

Real-time, three-dimensional prototype regional/mesoscale precipitation prediction studies for Colorado have been conducted for more than ten years (Cotton et al. 1994, 2004). These simulations used the CSU RAMS model with bulk microphysics (Walko et al. 1995) and horizontal grid resolutions between 16 and 80 km. Bruintjes et al. (1994) completed research forecast simulations of heavy precipitation events using horizontal grids as fine as 2 km. These simulations also used bulk microphysics and non-hydrostatic dynamics with interactive grid-nesting to focus on areas of interest. The model showed good correlation between model precipitation dynamics and the observations. Their results indicated that a seeder-feeder mechanism enhanced precipitation that contributed to flash flooding. It is important to note that in order to accurately simulate gravity wave-cloud interactions and frontal cloud bands and subsequent precipitation development, horizontal grids of 2 km were needed.

4.2 Important Issues for Project Design

Based on the background provided in the previous paragraphs the following important issues need to be addressed in terms of designing a winter orographic cloud seeding experiment in the Wind River Mountain Range and the Medicine Bow/Sierra Madre Mountain Ranges:

1. Characterization of wind flow patterns, cloud structures and associated precipitation in the area during different precipitation events using numerical modeling results and comparing these to observations to gain confidence that the models can simulate natural conditions with sufficient accuracy.
2. Based on the characteristics of the cloud and precipitation structures (from observations and numerical model simulations), evaluation of ground-based seeding strategies using numerical model simulations to develop seeding techniques that could effectively target SLW regions in the clouds that would develop into precipitation that would fall in the desired areas.
3. Development, validation and verification of the hypothesis that upstream quadrant releases of silver iodide actually do reach the impact areas. Local orography may be creating nonlinear flow patterns such as wake effects and eddies, which could potentially cause the seeding plumes to diverge from the targeted clouds.
4. Determination of the number of generators and/or aircraft that will be needed to target liquid water content regions in the two target areas.
5. Determination of which observational tools are essential and/or most helpful in designing, conducting and evaluating seeding operations.

Addressing these issues will help optimize the seeding strategies in the following regards:
- Improving locations of seeding equipment
- Improving timing of silver iodide release
- Improving selection of which generators to activate
- Providing more selectivity on when to seed, based on cloud composition

4.3 Approach

As stated previously, early experiments in snowpack augmentation generally involved randomized seeding and statistical analysis of precipitation analysis, but lacked information regarding local wind flow patterns over the area of interest. Two factors intrinsic to the cloud seeding process are dependent on this airflow. The production of SLW depends on the interaction of the airflow with the topography. The dispersion of seeding material is dependent on horizontal and vertical advection. Incomplete knowledge of the local wind patterns makes it difficult to predict if the material will enter the regions of SLW. Over the past decade, mesoscale models have been used to understand this complex problem (Bruintjes et al. 1995, and Cotton et al. 2004).

Bruintjes et al. (1995) compared observations of tracer dispersion in a mountainous region of central Arizona with simulations using a two-domain Clark model with minimum grid spacing of 2 km. They found that the location of SLW within a cloud was constantly changing but a model set-up with 2 km grid spacing was sufficient to capture the cloud water evolution and tracer dispersal. Cotton et al. (2004) described a model configured to investigate the differences between seeded and non-seeded simulations. These were done with a three domain Regional Atmospheric Modeling System (RAMS) model located over the mountains of Colorado (minimum grid spacing: 3 km). Their study extended the RAMS model by adding an additional Ice Freezing Nuclei (IFN) source and sink. The source term represented concentrations of

silver iodide produced by ground generators. The sink term represented the activation of silver iodide as primary ice.

This study was designed to apply the technique of fine-scale (minimum grid spacing of 1 km) mesoscale modeling to assess the potential for cloud seeding in Wyoming. It follows the approach put forward by Bruintjes et al. (1995) for this initial feasibility study. The first step is to set up a modeling system to complete these simulations. The Weather Research and Forecasting (WRF) modeling system developed through a collaborative community effort led by the National Center for Atmospheric Research (NCAR) was selected for this study for four reasons:

1. It is a community model that is free to anyone who wishes to download and use it.
2. It is characterized by improved numerical stability over steep topography.
3. It is relatively easy to implement on distributed-memory modeling systems, and
4. The addition of passive tracers to the model is straightforward.

The second step was to extend the model to include a passive tracer to represent the seeding material. The third step was to perform simulations to determine how precise the generator siting must be and to provide operational criteria. The fourth step includes the extension of tracer deployment to allow for multiple generators and timed releases. If time had allowed, a final step would have been to modify the code to activate the passive tracer (as an ice nucleant), consistent with the present knowledge of the behavior of silver iodide in clouds. This final step was beyond the scope of what could be preformed in the time allotted for this initial feasibility study.

4.4   Numerical Model Set-Up

The Weather Research and Forecast (WRF) modeling system is a rapidly developing model. At the time this investigation began WRF version 1.0.3, which offered no nesting capability, was available. This version was adopted for the initial model set-up. In the middle of June 2004 WRF version 2.0 was released, bringing with it nesting capability and an improved initialization package. This was quickly updated to versions 2.0.1 and 2.0.2 to fix initial software bugs. WRF version 2.0.2 was adopted for use on this project at the end of June 2004 and has been used for the remainder of this study.

The model was initially set up to run on a single computer processor and then moved to the more complex distributed memory (multi-processor) system. WRF v1.0.3 was initially used for runs either on the coarsest domain for a quick look, or on the finest domain to see how the tracer spreads. These runs were completed using a prototype microphysics package reported in Thompson et al. (2004). Subsequent sensitivity tests indicate this scheme may produce a more realistic distribution of cloud water, small primary ice, and snow. Details of this and other microphysics packages used in this study are given later in this section.

4.4.1   Domain Configuration

Initially, a three domain configuration of WRF v2.0.2 was set-up to study the small scale flow patterns over both the Wind River and Sierra Madre/Medicine Bow Regions (Table 4.2). Domain 1 uses 72 x 72 grid points with 9 km grid spacing, to cover a 4.2×10^5 km^2 area, including the majority of Wyoming and portions of surrounding states. Domain 2 nests in on the area of interest using 96 x 96 points with 3 km resolution. Finally, Domain 3 focuses on each region of interest using 144 x 144 points at 1 km grid spacing. Figure 4.1 shows the three grid

configuration for the Medicine Bow/Sierra Madre region. The Wind River configuration uses the same size domains but is focused over the Wind River Range.

Table 4.2 - Details of the Grid Configuration for the Three Domain Set-Up

Domain #	Grid Spacing	Grid Size	Center Latitude		Center Longitude	
			WR	MB	WR	MB
1	9 km	72 ×72	43.0	41.25	109.8	107.1
2	3 km	96×96 (97×97)	43.0	41.25	109.4	106.6
3	1 km	144×144(145×145)	43.0	41.25	109.4	106.6
WR denotes Wind River Range, **MB** denotes Sierra Madre/Medicine Bow Ranges						
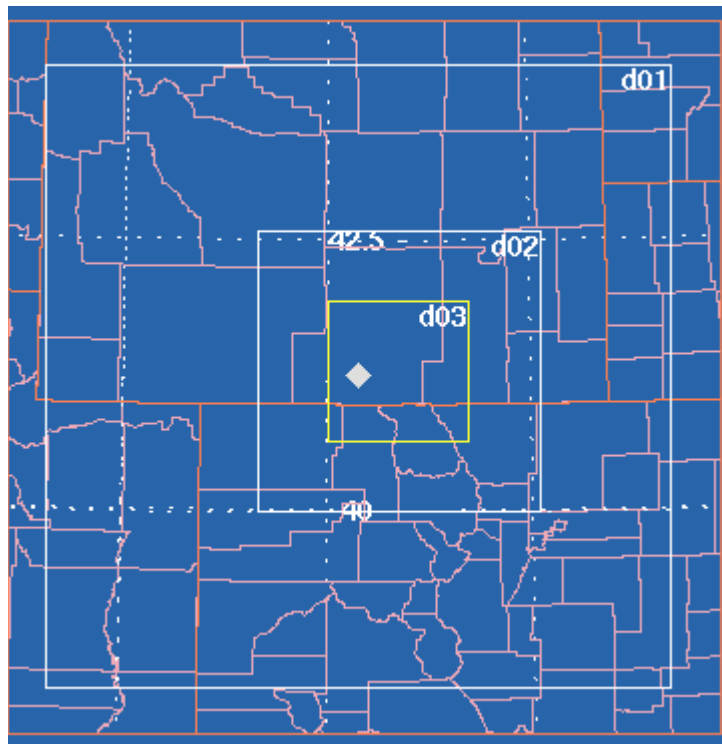
Figure 4.1 - Example of the three domain configuration for the Medicine Bow/Sierra Madre region. The Wind River configuration used the same sized grids with the center latitude/longitude shifted to the northwest.

Baseline simulations initialized on 5 February 2004 for the Wind River area of interest were conducted. Results for these simulations were presented at the scoping meetings held 16-19 August 2004 and are reported in Section 4.5. A simulation for the Medicine Bow area of interest was initially completed and showed that the low pressure system, which was providing the forcing for the snowfall moved out of the area shortly after the initialization at 00 UTC on 5 February 2004. It was decided to increase the configuration to include a fourth domain to include the western half of the United States to better simulate the synoptic scale. Using a 3:1 nesting ratio, the new, larger Domain 1 grid spacing was 27 km.

Original plans for the four domain simulations included a second and third domain that included the entire state of Wyoming. However, computational memory constraints dictated that these domains be scaled back to match the sizes of the original three domains. Details of the four domain configuration are provided in Table 4.3. A visualization of grid configurations for Wind River and Medicine Bow/Sierra Madre Ranges are given in Figures 4.2 and 4.3 respectively. Similarly, the topography resolved by each domain may be seen in Figures 4.4 and 4.5.

Table 4.3 - Summary of initialization grids, both proposed (4 grid) and currently used (3 grid)

Domain #	Grid Spacing	Grid Size	Center Latitude		Center Longitude	
			WR	**MB**	**WR**	**MB**
1	27 km	110x90	43.0	41.25	109.8	107.1
2	9 km	72 ×64	43.0	41.25	109.8	107.1
3	3 km	97×97	43.0	41.25	109.4	106.6
4	1 km	160x160	43.0	41.25	109.4	106.6
WR denotes Wind River Range, **MB** denotes Sierra Madre/Medicine Bow Ranges						
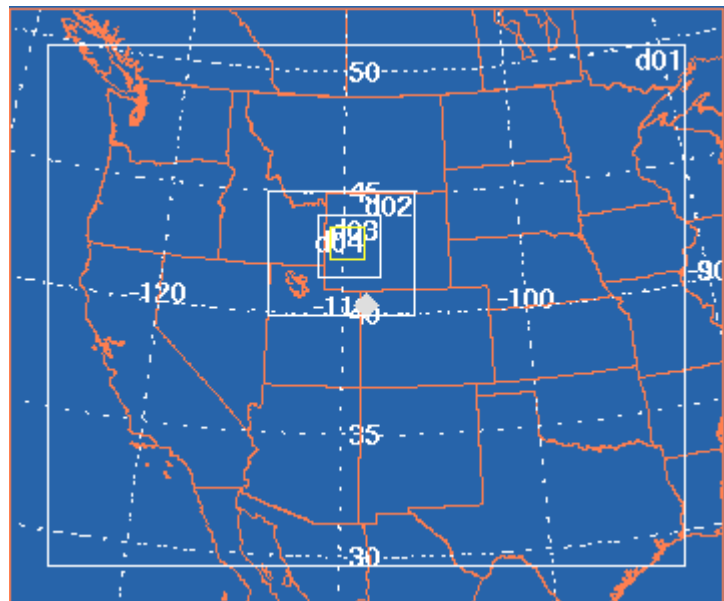
Figure 4.2 - Set up for the four-domain simulation for the Wind River region.
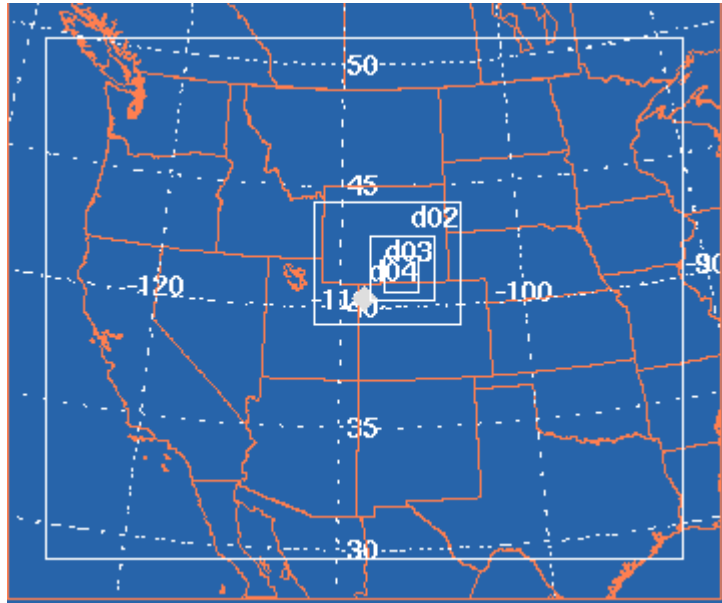
Figure 4.3 - Set up for four domain simulation for the Medicine Bow/Sierra Madre region.

4.4.2 Computing Platforms

For simplicity, the initial simulations were performed on a single processor. Single processor simulations using the 3 domain configuration were found to take approximately 1 week to complete per 24 hour run. For this reason, the modeling system was transitioned to a 13-node, 26 processor, and distributed memory system for quicker completion of simulations. Three domain simulations on the 26 processor system took 1 hour to complete 1 hour of simulation time. Hence the move to the multi-node processor system represents a large savings in computation time but does add to the complexity of the system development.

The WRF user's workshop and tutorial were attended by co-author (and NCAR modeler) Tara Jensen between 22 June 2004 and 30 June 2004. Information obtained during these two events was instrumental in the initiation of transition to distributed memory machine. The standard initialization programs and model executables were successfully built and tested on a Linux cluster located at NCAR. The cluster has a Debian operating system and the potential for 26 separate processors to perform model calculations.

The WRF architecture is designed for the distributed memory processing environment. The system was designed to auto generate the decomposition parameters for spreading the grid points across available nodes. It also invokes a "halo" region that handles the message- and parameter-passing between each node. Some of these parameters must be included during compilation and are designated by a "configure" command which allows the user to declare whether the model will be running on single or multiple processors. It allows for run-time selection of how many processors are used, allowing for quick changes in computing power without having to recompile. Documentation of how to set-up the WRF model for either scenario may be found online at www.wrf-model.org.

Figure 4.4 - Topography features resolved by Domain 1 (upper left), Domain 2 (upper middle), Domain 3 (upper right) and Domain 4 (lower left) of the Wind River Region.

Figure 4.5 - Topography features resolved by Domain 1 (upper left), Domain 2 (upper middle), Domain 3 (upper right) and Domain 4 (lower left) of the Medicine Bow/Sierra Madre regions.
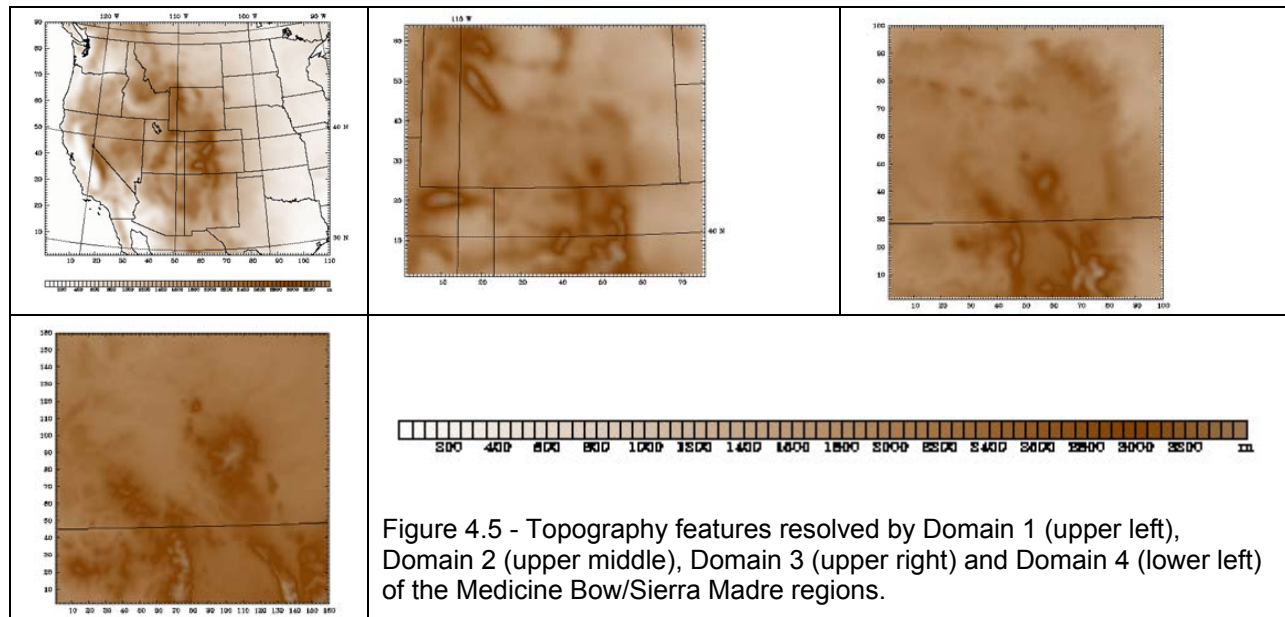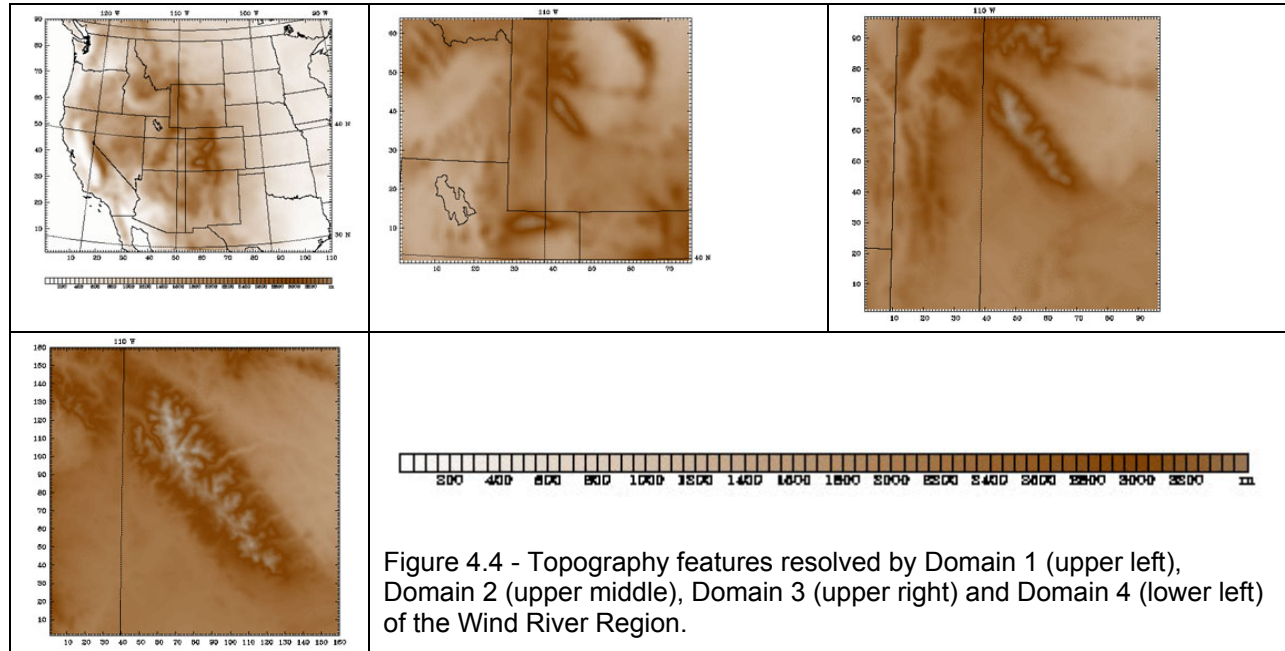
4.4.3 Modeling Physics

The WRF modeling system has been designed around an Eulerian mass coordinate system, similar to the ETA model. However, the numerics are significantly improved over many of the current mesoscale models. The developers determined that using a third order Runga-Kutta solver rather than the leap-frog scheme implemented in the PSU-NCAR MM5 would allow for longer time steps, greater numerical stability, and better handling of steep topography. The infrastructure is also designed so that there is no longer a requirement to nest with a 3-to-1 grid spacing ratio nor a 3-to-1 time step ratio. These benefits are evident over the steep topography in Wyoming. The physics selected for these simulations were primarily the standard options for

WRF. These are summarized in Appendix A. Sensitivity runs were performed to evaluate the cloud microphysical modules available in the standard release of WRF and to compare them with a prototype module described in Thompson et al. (2004). Because of the nature of this investigation, the minimum number of predicted mixing ratio of hydrometeor species the microphysics package should include water vapor, cloud liquid water, primary ice, and snow. Table 4.4 summarizes the details of the four cloud microphysical packages that meet these criteria. Results of these sensitivity studies are discussed in Section 4.5.

4.4.4   Initialization Data

The model was initialized using grids from the ETA AWIPS 40 km reanalysis obtained from the NCAR/Research Applications Laboratory mass storage files. These data are also available from the following location on the web: *http://aftp.fsl.noaa.gov./divisions/frd-laps/WRFSI/Geog_Data.*

Boundary conditions for Domain 1 were generated over a 48 hour period with 3 hour increments. The nesting algorithm requires only initial conditions be present for more domains. These were created from initial ETA model grids. Topography, land use, and soil type are derived from US Geological Survey grids with 30 s (latitude and longitude) resolution. The percentage of land versus water is provided in 10 m increments, and soil temperature in 1 degree (latitude and longitude) files. Albedo, green fraction, and maximum snow albedo are derived from 10 minute files. These are all used to make up the lower boundary condition for the model. These data are described online in the WRF Users Guide and available at: *http://www.mmm.ucar.edu/wrf/users/docs/user_guide/contents.html.*

Table 4.4 - Microphysics options considered for use in this study.

Module	WRF Single Moment - 6	WRF Single Moment - 5	Lin	Thompson
Abbreviation	**WSM6**	**WSM5**	**-**	**-**
Predicted mixing ratio comprised of:	Water vapor Cloud water Rain Primary Ice Snow Graupel	Water vapor Cloud water Rain Primary Ice Snow	Water vapor Cloud water Rain Primary Ice Snow Graupel	Water vapor Cloud water Rain Primary Ice Snow Graupel
Number Concentration	Diagnosed	Diagnosed	Diagnosed	Predicted
Reference	Hong et al. 2004	Hong et al. 2004	Lin et al. 1983	Thompson et al. 2004

4.4.5   Addition of Tracer

The addition of a passive tracer to a mesoscale model can be very complex. Many times, there are global variables that need to be added along with additional modules to handle mass continuity. Working Distributed memory code adds additional complexity because of the addition of domain decomposition variables. The WRF architecture was designed to auto generate some of the code necessary to make modules and/or additions of variables compatible with the distributed memory set up. This feature allows for a relatively easy extension of the standard physics package to include a passive tracer for both single processor and distributed memory. Four modules needed to be modified to facilitate the tracer. These included the block

of variable common to the model (Registry/Registry.EM), the solving routine for the dynamic core (dyn_em/solve_em.F), the microphysics driver (phys/module_microphysics_driver.F) and the WSM6 (WRF Single-Moment 6) microphysics routine (phys/module_mp_wsm6.F or phys/module_mp_drizzle.F). Appendix B detail the changes made to these routines.

The Registry is where all common variables are defined. It has information about how each variable should be handled in the dynamics solver, how it should be mapped on the horizontal and vertical grids, how the boundary conditions should be handled and how it should be passed across the decomposed boundary when running in distributed memory. Over thirty-thousand lines of code are automatically generated from the registry. Please refer to the WRF Users Guide, available online at: *http://www.mmm.ucar.edu/wrf/users/docs/user_guide/contents.html* for a more detailed description of how the Registry works. A chem scalar, called "qnt" in the model and "QNTRACER" in the netCDF output file was added to the model by first putting it in the Registry. It was also added to the call to the microphysics driver in the sovle_em.F routine.

The representation of glaciogenic seeding material as a passive tracer with release rate of 2.4×10^{16} nuclei/hour (Arizona Dept. of Water Resources 1989) was originally introduced into the WRF code in the Thompson microphysics module. Therefore the tracer was coupled with a microphysics option that does not currently work across multiple nodes on the cluster. It was decided to couple the tracer with a microphysics package that was working on the cluster, WSM6. Like the Thompson routine, WSM6 includes prognosis on the mixing ratio of six primary hydrometeor species, including rain, cloud water, pristine ice, snow, aggregates, and graupel. Results in the following discussion are primarily based upon the use of the implementation of the tracer in the WSM6 microphysics module.

The microphysics driver is where the model identifies which microphysics package to use, based on the number selected in the model set-up file called namelist.input, and calls that routine. The variable was added to the call for WSM6 subroutine in module_ microphysic_driver.F. Finally, the chem scalar is passed into module_mp_{type}.F. In the WSM6 module, the scalar was additionally passed into a subroutine that makes the microphysics calculations along a longitude belt (WSM62D). It is here that the point source of the passive tracer is implemented. The location of the point source is designated by "iloc", "jloc", and "kloc", which are assigned at the beginning of the WSM6 module. The "iloc" selected the location in the x direction (along a latitude belt). Similarly, "jloc" selects the location along the longitude belt". The variable "kloc" specifies at what altitude the tracer is released. By modifying the "kloc" variable, one can simulate either ground based generation or aircraft based generation. In the very near future, an "itimestart" and "itimestop" will also be added to the model to simulate the turning on and turning off the generators. At this time, the modifications to location must be made and then the code is recompiled. Multiple locations may be included by having several "iloc, jloc, and klocs". WRF developers promise a name list option will be made available sometime in the next year or so which will allow for modification of tracer release locations without recompiling.

4.5   Baseline Simulations

The news bulletins posted on the Riverton Wyoming Forecast Office website (http://www.crh.noaa.gov/riw/News_Archives.htm) were used to identify potential case studies. This website indicated the snow event on 7-9 February 2004 produced ample precipitation and that 27-29 February 2004 was a very strong snow event resulting in major road closures. Snowfall records from the MesoWest website (http://www.met.utah.edu/mesowest) and U.S.

Department of Agriculture NRCS Wyoming SNOTEL website (http://www.wcc.nrcs.usda.gov/SNOTEL/Wyoming/wyoming.html) substantiates these observations and provided an additional, weaker, event on 4-6 February 2004.

4.5.1 Synoptic Validation

Simulations were made using Domain 1 for each of the three cases and are presented in Figures 4.6, 4.7, and 4.8. Each figure provides the WRF simulated and NWS observed sea level pressure fields (upper panels), the 500 mb fields (middle panels), and the WRF simulated accumulated precipitation in the lower left for 12 hours into each simulation. The simulations are based solely on the ETA model input at the boundaries and the WRF Eulerian Mass core solutions. There has been no inclusion of observations for nudging purposes.

The snow event on 4-6 February 2004 produced small to moderate snowfall accumulation for both areas of interest. Comparison with modeled and observed sea level pressure charts indicates center of the simulated low pressure system, minimum 1000 mb, is a little too far north in Colorado but is quantitatively comparable to the observed low with a minimum pressure of 999 mb. The observed temperatures ranged from 14°F in northeastern Wyoming to 18-22 °F near the Wind River Basin and to the south. The WRF model simulated similar values. Observed synoptic station surface winds were basically light with a north-easterly component between the Wind River and Medicine Bow/Sierra Madre Ranges. The winds were similar in the simulation. The simulated 500 mb trough is co-located with the observed 500 mb analysis shown in the middle section of Figure 4.6. However, the central low is 30 meters deeper than observed. This bias was introduced at initialization and remains consistent throughout the next 12 hours. At 12 UTC on 4 February, the precipitation accumulated by the model and shown in the lower panel, indicates it was a slightly more significant upslope event for southeastern sections of both areas of interest.

A moderate snow event occurred between 7 and 9 February 2004. Domain 1 was initialized at 12 UTC on 7 February 2004. Figure 4.7 shows the 12 hour model simulated fields at 00 UTC on 8 February 2004. The surface low in Colorado is placed correctly, however the front extending up to the primary low in Saskatchewan is located approximately 50 km too far east. The simulated Colorado low is approximately 1008 mb while the observed low is 1014 mb. The resultant wind speeds near the front are 3 times too strong on Domain1. Away from the front, in western Wyoming, the simulated wind speed and direction is more consistent with observations. Temperatures are a few degrees too cold throughout most of Wyoming. The location of the 500 mb low is well placed in the simulation but has a geopotential height of 5480 m versus the observed height of 5500 m. This 20 meter bias was present at the initialization and is maintained. Simulated wind direction is similar to the observed but the speed is approximately 10 m s^{-1} too slow. The simulated accumulated precipitation field indicates the precipitation from this system is moving into the northwestern part of the state, impacting Wind River and some residual precipitation from the previous storm is impacting the Medicine Bow/Sierra Madre Range.

The snow event on 28-29 February 2004 was a large event according to the Riverton Forecast Office news page. The 12 hours simulated and observed surface and 500 mb fields are provided in Figure 4.8. The position of the primary low in Utah is too far north and too deep. At 00 UTC on 8 February 2004, the observed low is 1004 mb and the simulated is 1002 mb. However, a low that extended across northeastern Wyoming is fairly well placed. Observed temperatures across Wyoming are warmer than in the previous two cases (30-45°F) and the

simulations follow this trend. However, temperatures over the western topography range from 20-28°F where the observed temperatures are 30-38°F. Wind speeds and directions are similar to observed winds. The placement of the 500 mb low is consistent with the observed 500 mb low, however, as in the previous simulations, there is a -30 meter bias in the simulated fields that was there at initialization. The simulated precipitation field indicates Wind River should already be experiencing heavy precipitation at 00 UTC on the 8 February 2004.

In general, the model provides a good representation of the synoptic setting on all three cases selected for initial investigation. The 20-30 meter bias at 500 mb is actually present at 700 mb and 300 mb.   This is an artifact of the standard initialization package and needs to be investigated further. Also, inclusion of soundings and surface observations into the initialization would help correct this bias. This option should be integrated into the modeling system in the future.

Model Results

Observations

WRF MASS Forecast   2004-02-04 12:00:00

Rainfall (mm)
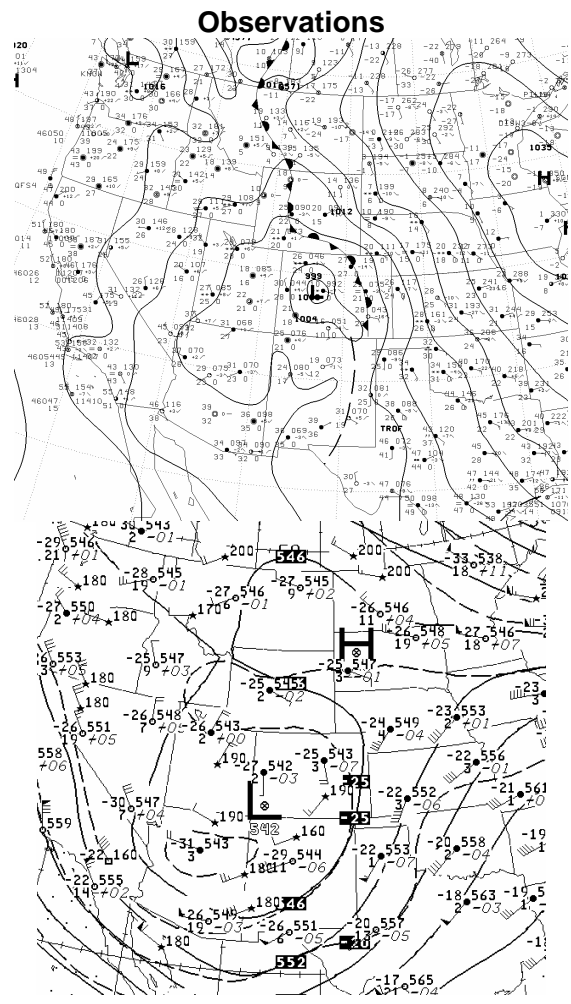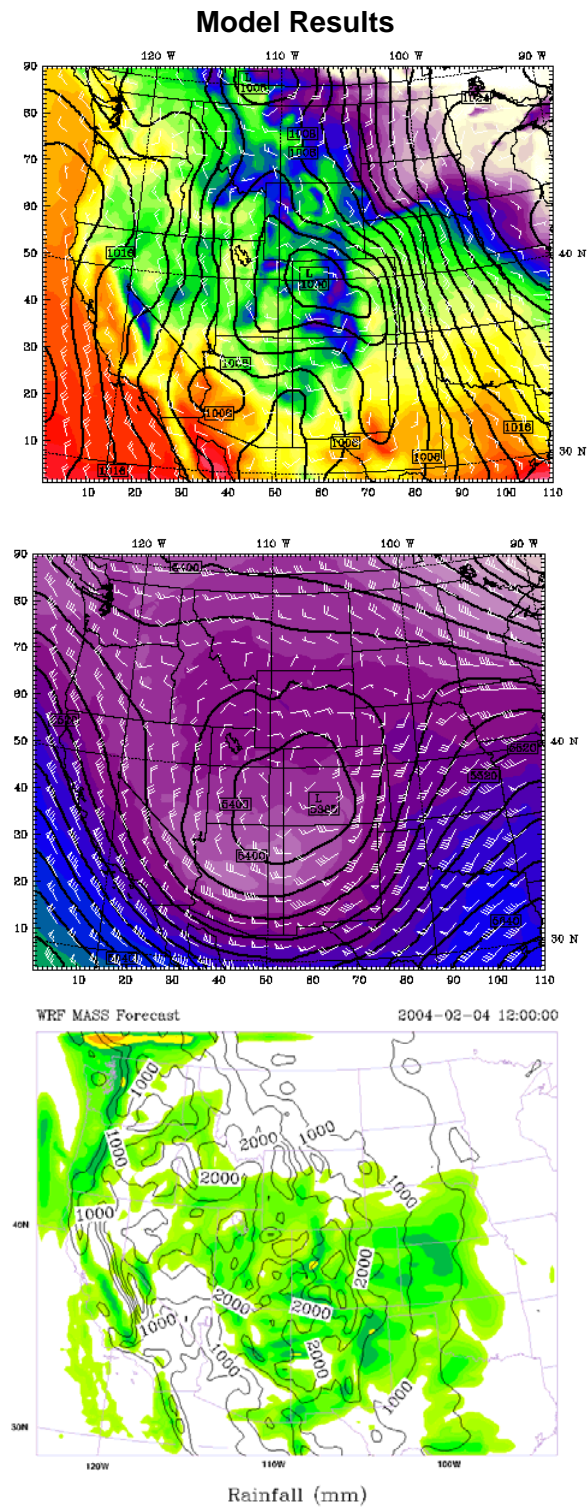
Figure 4.6 - Sea Level Pressure (top), 500 mb analysis (middle), and accumulated precipitation (bottom) at 12 UTC on 4 February 2004. These plots are from Domain 1 from simulations initialized at 00 UTC on 4 February 2004. Observations courtesy of NWS. Color Keys are below:
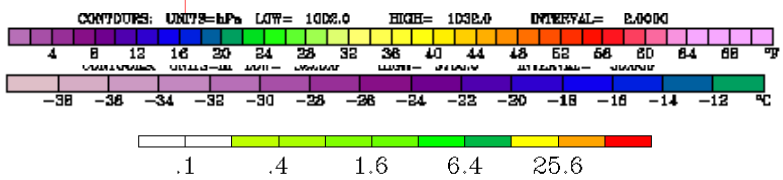
Sea Level Temperature (F)

500 mb Temperature (C)

Precipitation (mm)

Model Results
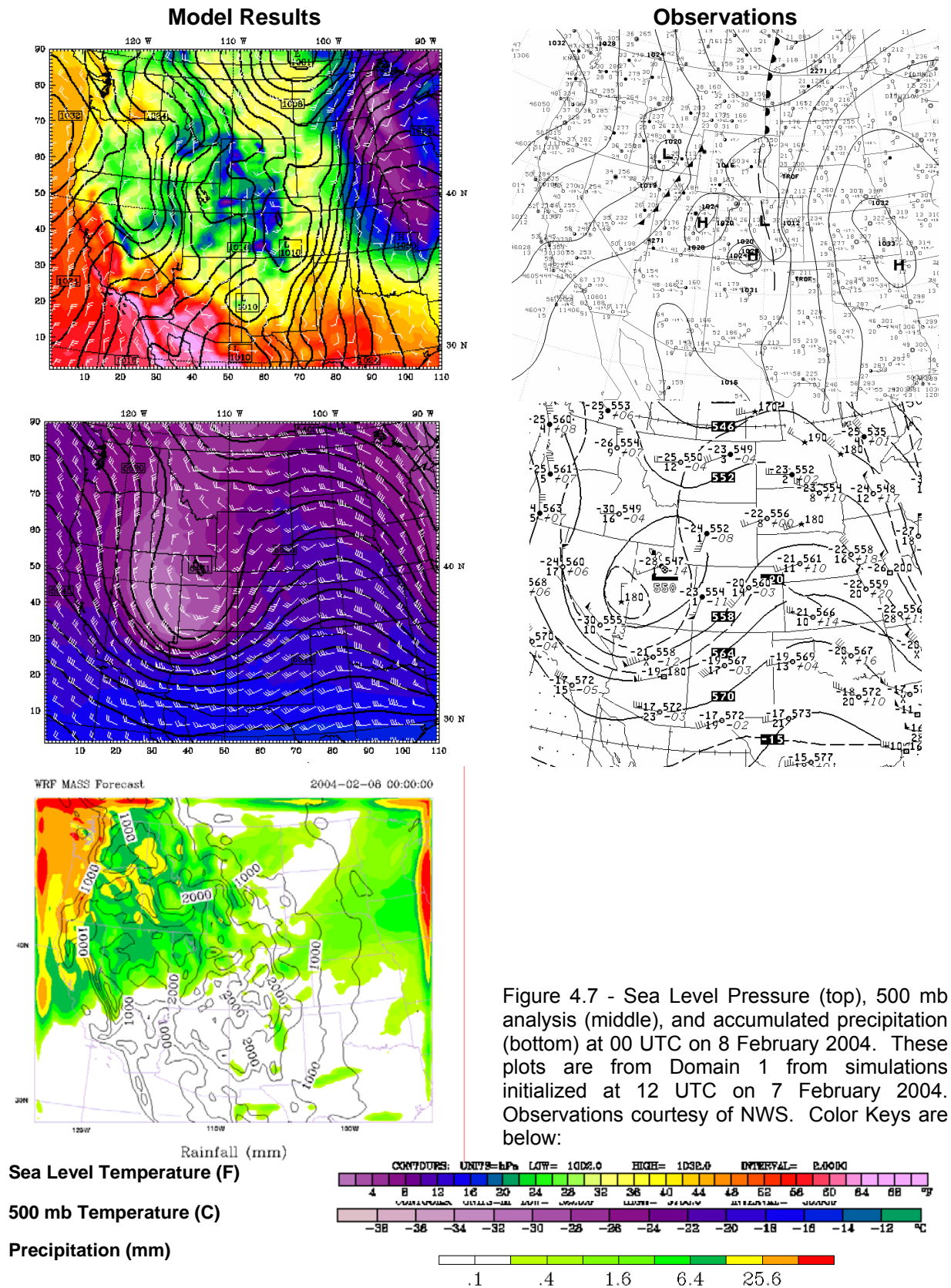
Observations

Figure 4.7 - Sea Level Pressure (top), 500 mb analysis (middle), and accumulated precipitation (bottom) at 00 UTC on 8 February 2004. These plots are from Domain 1 from simulations initialized at 12 UTC on 7 February 2004. Observations courtesy of NWS. Color Keys are below:

Sea Level Temperature (F)

500 mb Temperature (C)

Precipitation (mm)

Model Results
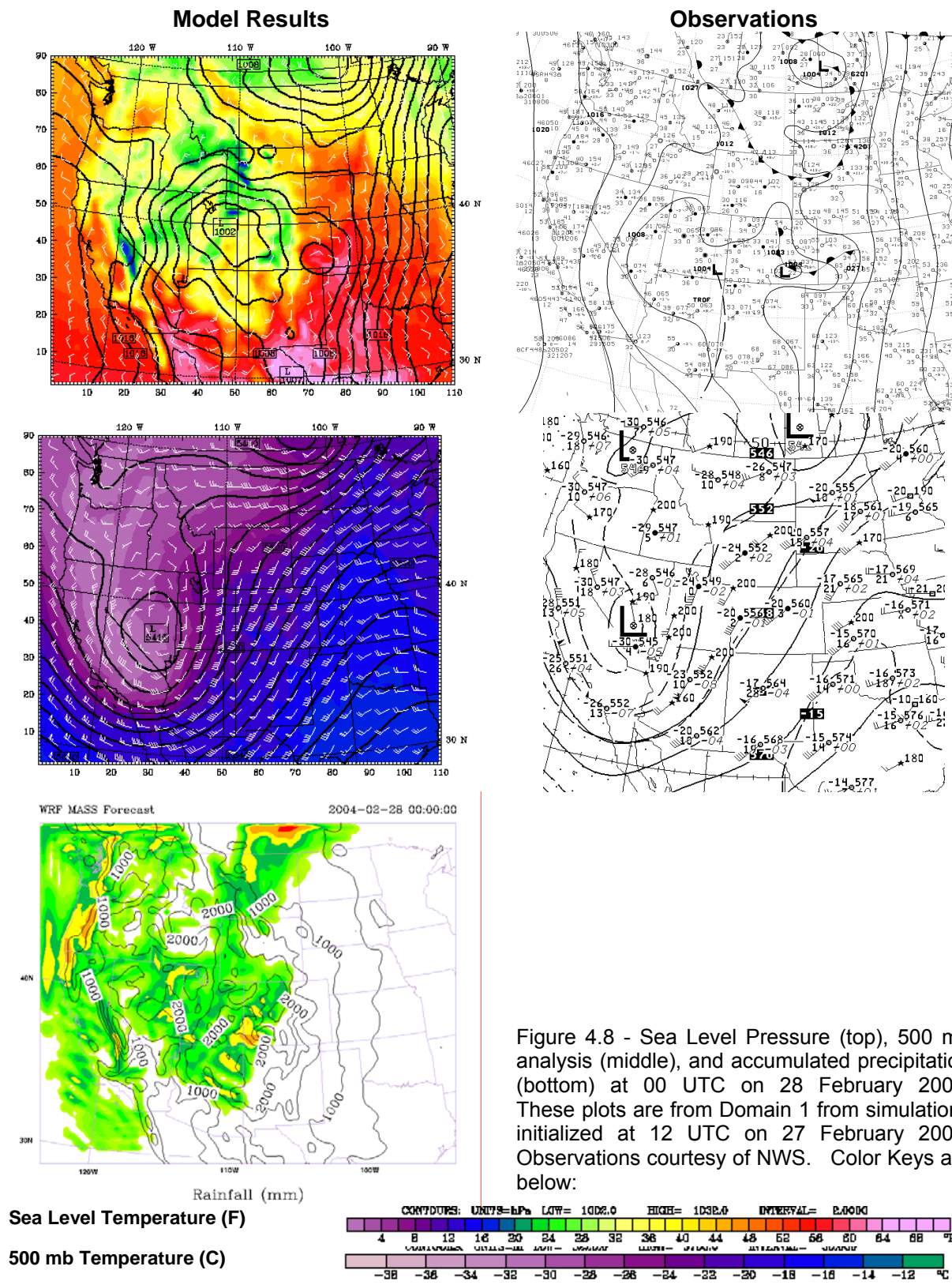
Observations

Figure 4.8 - Sea Level Pressure (top), 500 mb analysis (middle), and accumulated precipitation (bottom) at 00 UTC on 28 February 2004. These plots are from Domain 1 from simulations initialized at 12 UTC on 27 February 2004. Observations courtesy of NWS.   Color Keys are below:

Sea Level Temperature (F)

500 mb Temperature (C)

Precipitation (mm)

.1	.4	1.6	6.4	25.6	
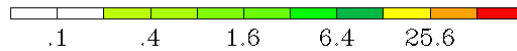
4.5.2   Sensitivity to Microphysics Modules

Sensitivity runs were performed to evaluate the cloud microphysical modules available in the standard release of WRF and compare them with a prototype module described in Thompson et. al (2004). This was done, in part, to determine if time needed to be committed to making the Thompson and Lin schemes work on the cluster. The emphasis of this investigation is on presence of super-cooled liquid water. To capture this atmospheric phenomenon, a minimum number of predicted mixing ratio of hydrometeor species the microphysics package should include: water vapor, cloud liquid water, primary ice, and snow. Table 4.4 summarizes the details of the four cloud microphysical packages that met these criteria. Results of sensitivity studies, based on a 12 UTC initialization on 7 February 2004 of the Wind River configuration (Table 4.3), are presented here. Two of the modules, WSM6 and WSM5, differ by only the inclusion of graupel mixing ratio. For this reason, only results from WSM6, which produced more cloud liquid water (Lin and Thompson scheme), are included in the comparisons.

The mixing ratios of cloud water, primary ice, and snow, predicted on Domain 2 are presented in Figures 4.9 to 4.11 respectively. The Thompson module (bottom left panels) developed the greatest amount of liquid water near the surface but little to no primary ice and moderate amounts of snow. The Lin scheme developed small amounts of all three species during the 12 hours of simulation.
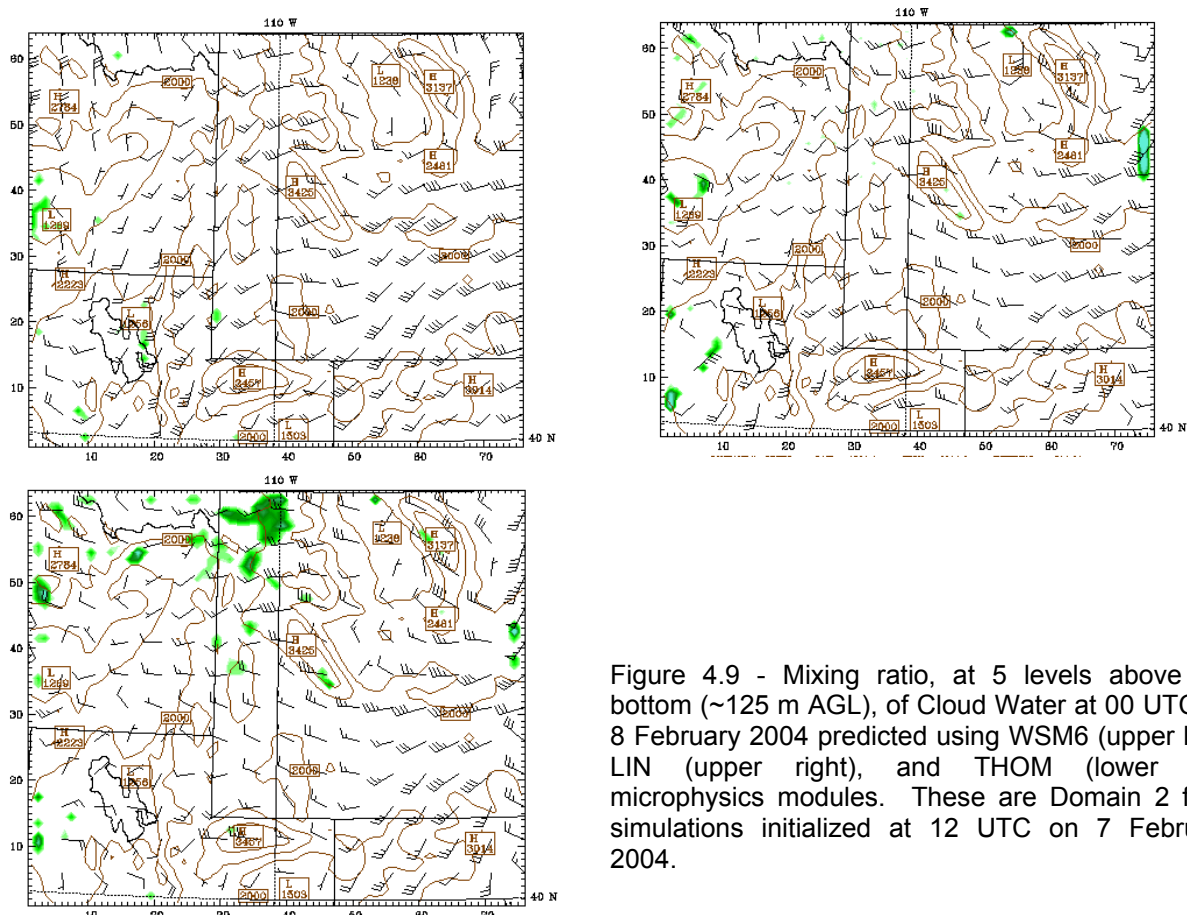
Figure 4.9 - Mixing ratio, at 5 levels above the bottom (~125 m AGL), of Cloud Water at 00 UTC on 8 February 2004 predicted using WSM6 (upper left), LIN (upper right), and THOM (lower left) microphysics modules. These are Domain 2 from simulations initialized at 12 UTC on 7 February 2004.

Cloud Water Mixing Ratio (g kg⁻¹)

Figure 4.10 - Mixing ratio, at 5 levels above the bottom (~125 m AGL), of Ice at 00 UTC on 8 February 2004 predicted using WSM6 (upper left), LIN (upper right), and THOM (lower left) microphysics modules. Simulation was initialized at 12 UTC on 7 February 2004.

Ice Mixing Ratio (g kg⁻¹)
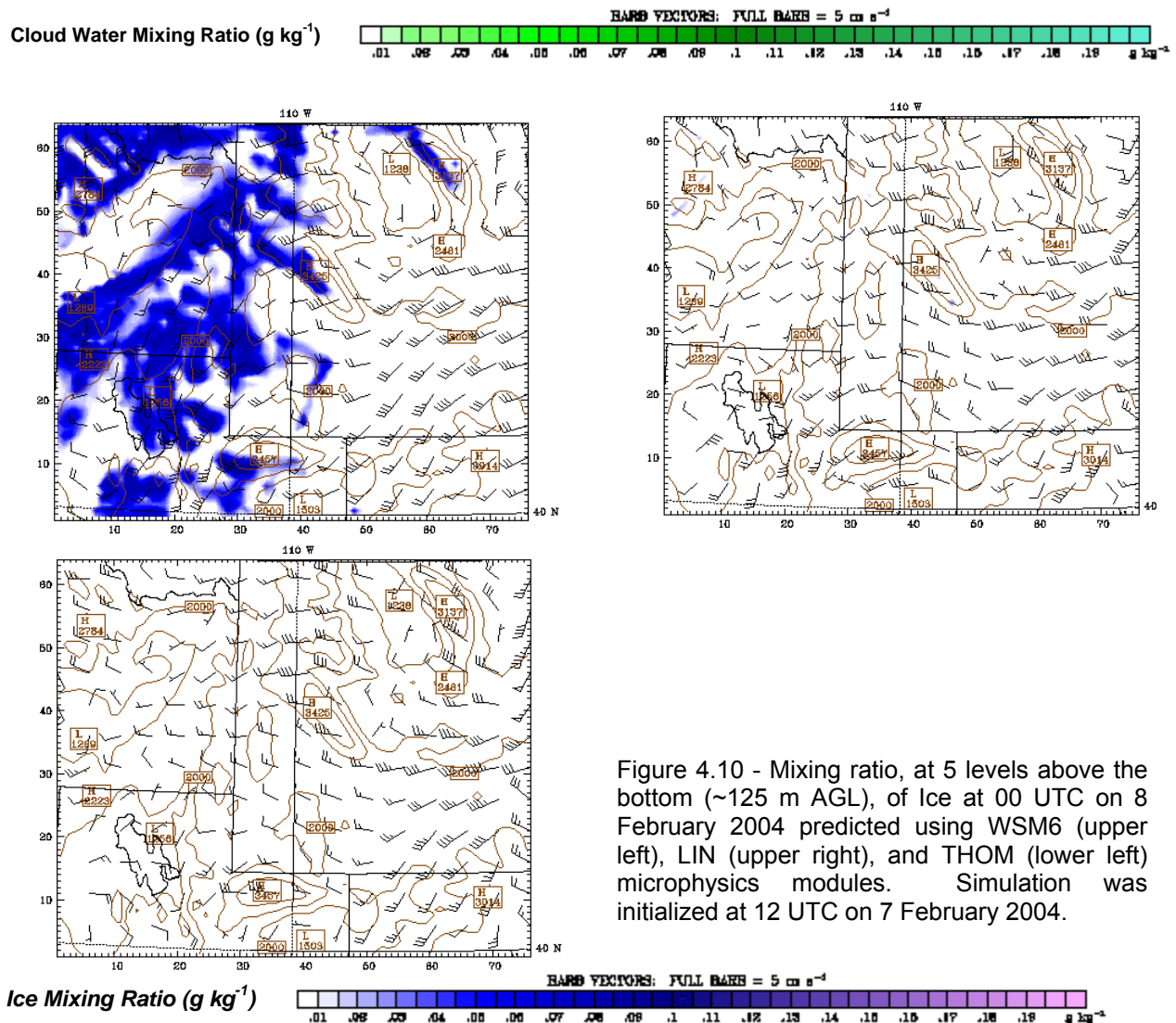
The WSM6 scheme developed no cloud water in Wyoming at 25 m AGL but generous amounts of primary ice. Temperatures at this level were approximately –5°C so the presence of large quantities of ice (0.2 g kg⁻¹) may be excessive in WSM6. This observation makes Lin and Thompson modules seem like better candidates. However, primary ice in both schemes was still not present at 5 km (-20 to –23°C). Primary ice should start developing naturally at approximately –10°C. Since running these simulations, discussion with the developer of the Thompson scheme suggested a slight modification to some of the parameterised variables in the scheme may improve the response of the Thompson scheme.

Snow Mixing Ratio (g kg⁻¹)
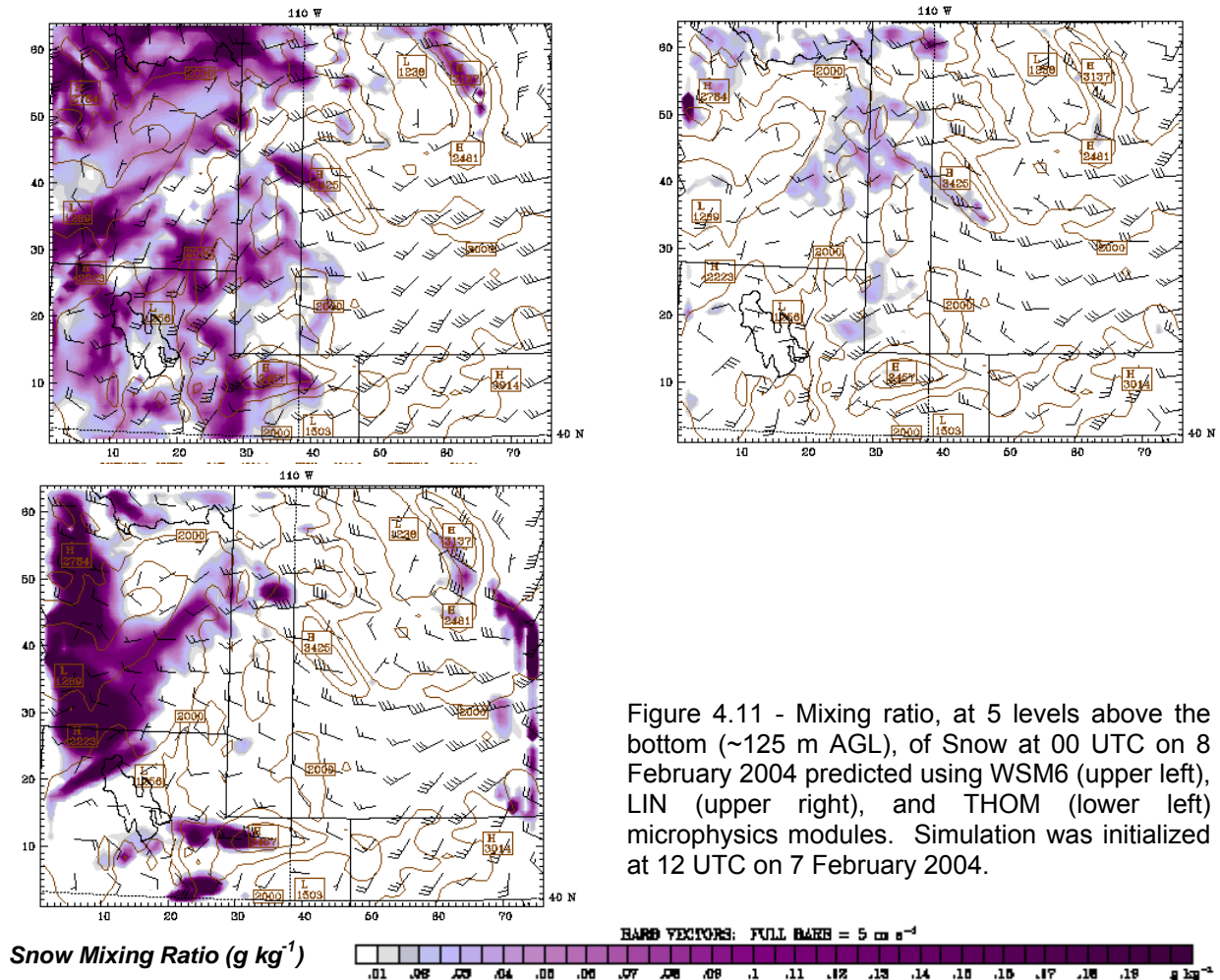
Figure 4.11 - Mixing ratio, at 5 levels above the bottom (~125 m AGL), of Snow at 00 UTC on 8 February 2004 predicted using WSM6 (upper left), LIN (upper right), and THOM (lower left) microphysics modules. Simulation was initialized at 12 UTC on 7 February 2004.

4.6   Tracer ("Seeding Material") Simulations

4.6.1 Single "Generator" Simulations

A single source of a passive tracer was used during the development and testing phase of this project. Figure 4.12 shows the tracer plume at two different times on 5 February 2004 at the lowest sigma surface in the model. It can be seen that the tracer stays fairly concentrated close to the source but is broadly dispersed further away. The dispersal of tracer also responds fairly quickly to changes in direction. This means that careful attention must be paid to the siting and operational procedures for each generator.
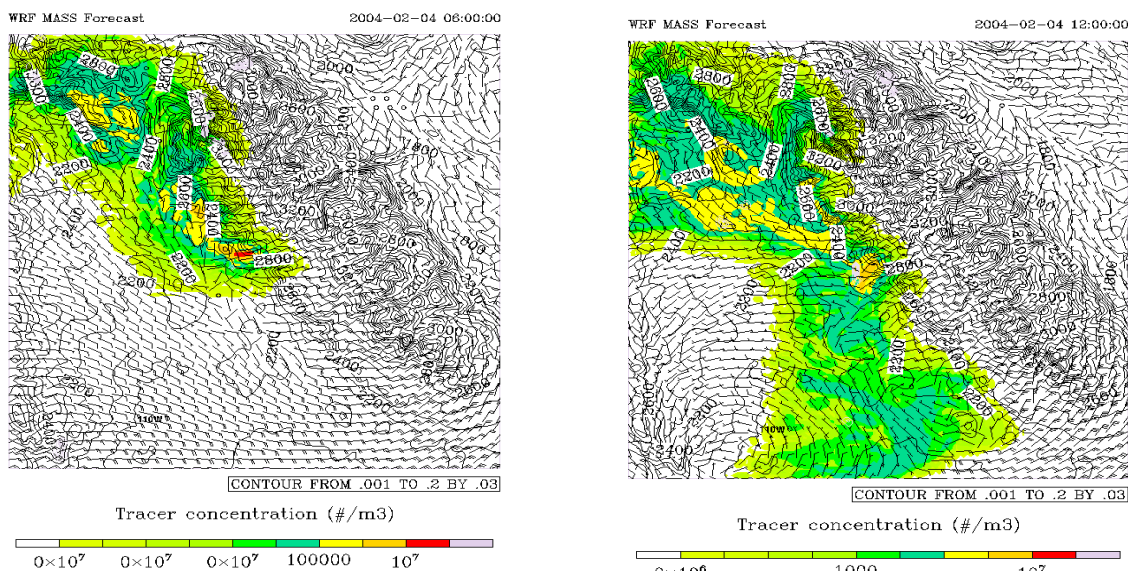
Figure 4.12 Tracer concentration released from one source, wind barbs in m/s, and terrain at the lowest level of the model at 06 UTC (left) and 12 UTC (right) on 5 February 2004. Plots are of Domain 4.

4.6.2   Multiple "Generator" Simulations

An operational program does not rely on only one generator to seed the target area. Additional tracer sources were implemented to represent multiple generators. This extension of the code was tested on the 7-8 February 2004 Wind River initialization. Two additional generators were added; one in the northwest and two on the southern side of the range.

Typical operational designs include strategically placing generators upstream of the target region and aligning these generators with the general local wind direction and speed in the region. This wind flow is generally obtained from larger scale model results. The four-grid configuration included two-way interactive nesting. This means that the tracer is passed from Domain 4 up to Domain 3, 2, and eventually 1. Figure 4.13 provides a snapshot of the simulated tracer on the four different Wind River domains at 12 UTC on 8 February 2004. In Domain 1, the wind flow is primarily northerly over the regions of interest and the tracer looks like a large oblate region over western Wyoming. A slight shift to north-northeasterly winds is resolved in Domain 2 as well as the concentration of the tracer on the southwestern side of the range. Domain 3 resolves a general northeasterly flow across the range with the hint of a mesoscale eddy on the upwind (eastern) side of the mountain. The 3 km grid spacing also allows for better resolution of the tracer path and concentration near each point source. As expected, Domain 4 provides much more information about the local structure of the winds and shows that the tracer remains highly concentrated in a thin line from the northern generator.

Tracer Concentration (#)
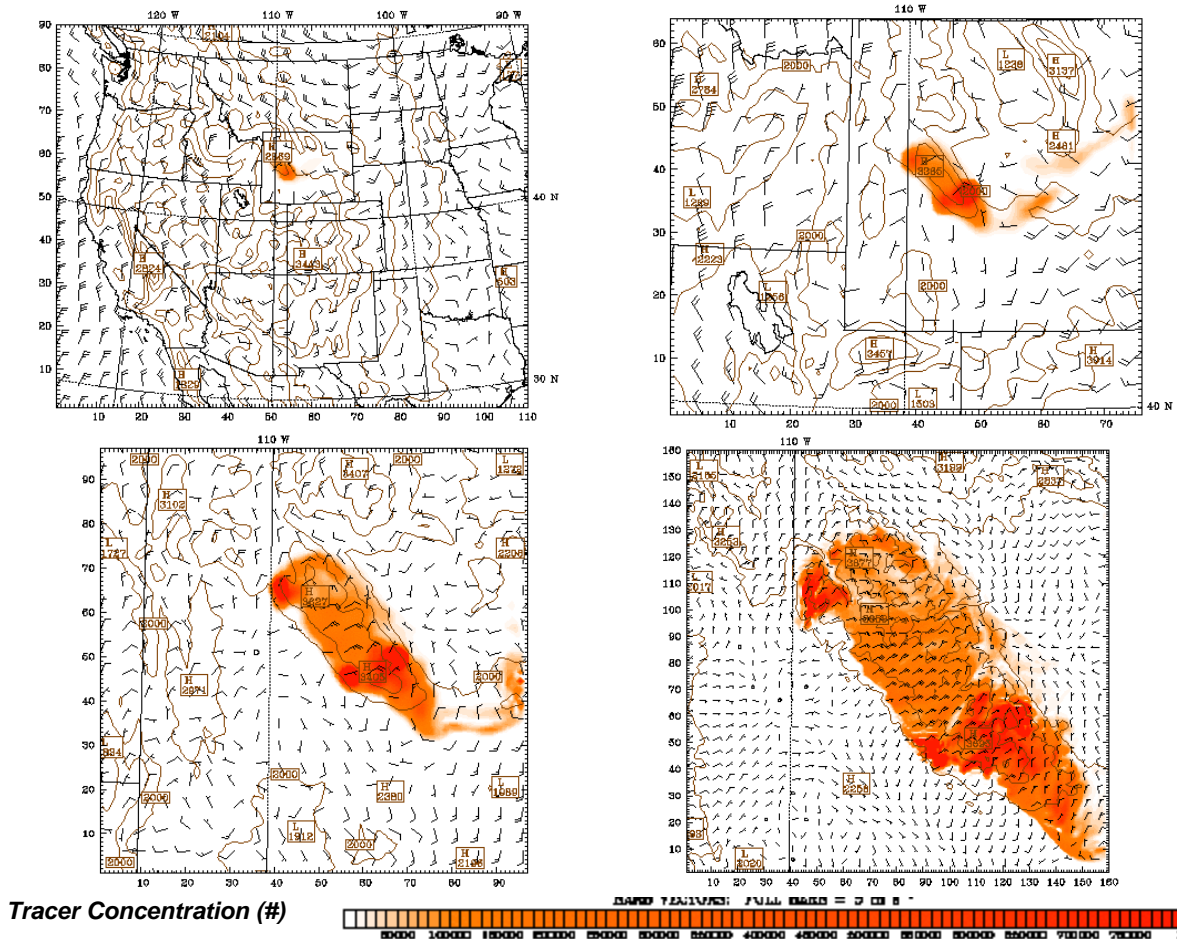
Figure 4.13 - Tracer concentration on Domain 1 (upper left), Domain 2 (upper right), Domain 3 (lower left), and Domain 4 (lower right) released from three source, wind barbs in m/s, and terrain at the lowest level of the model at 12 UTC on 8 February 2004.

4.7   Case Studies

The baseline simulations reported in Section 4.5 allowed the investigators to test the modeling system, find some of the weaknesses, and determine which date to investigate as the first case study. It was found that simulations of the strongest snowfall event, 27-28 February 2004, were unable to be completed using either domain configuration. The reason for these failures is still being investigated. The second strongest case, 7-9 February 2004, was then selected for the initial simulations, and the Wind River configuration was simulated first.

A low pressure system moved in from the northwest, bringing southwesterly flow into the remnants of the previous system, which then shifted north to northeasterly as the primary system passed to the south through Colorado. This produced upslope conditions on the western side of the range as the system moved into the area. The upslope later shifted to the eastern side. Snow fell across the northwest quadrant of Wind River region first, beginning around 12-14 UTC on 7 February (as indicated by SNOTEL measurements summarized in Table 4.5). It began across the southwestern section a few hours later (around 15 UTC). By approximately 00 UTC on the 8 February, the upslope conditions had ceased on the western

slope and moved to the eastern. Snow began falling in the southeastern sections by 5 UTC on the 8 February.

Table 4.5 - Summary of onset and termination of primary snowfall during 7-8 February 2004 (Source: Wyoming NRCS SNOTEL data)

Wind River Range	Approx. Start	Approx. Stop
Northwest	12 UTC on 7th	21 UTC on 7th
Southwest	15 UTC on 7th	22 UTC on 7th
Northeast	00 UTC on 8th	14 UTC on 8th
Southeast	05 UTC on 8th	20 UTC on 8th
Medicine Bow/Sierra Madre	**Approx. Start**	**Approx. Stop**
Sierra Madre-West	08 UTC on 8th	04 UTC on 9th
Sierra Madre – East	17 UTC on 7th	Variable
Medicine Bow – Southwest	17 UTC on 7th	23 UTC on 7th
Medicine Bow - Northeast	10 UTC on 8th	08 UTC on 9th

The snowfall pattern in the Sierra Madre/Medicine Bow region appears to be dominated more heavily than the Wind River Range by either local flow or 700 mb wind conditions. If low-level synoptic winds were driving the snow patterns, it would be expected that upslope conditions on the western side of the Sierra Madres would form snow before anywhere else. This is not the case. Analysis of SNOTEL data indicated that snow fell over the eastern portions of the Sierra Madres and Southwestern regions of the Medicine Bow range first (17 UTC on 7 February) and then proceeded to develop by 08-10 UTC on 8 February over the western portion of the Sierra Madres and northern portion of the Medicine Bow range. The latter development is consistent with the winds shifting to a northeasterly flow as the system slipped south through Colorado.

4.7.1   Wind River Range

The simulation was initialized at 12 UTC on 7 February 2004 using the Wind River configuration detailed in Section 4.4. Three point sources (generators) were activated at locations 105, 45; 50, 90; and 60,125 (from bottom of left axis, from left of bottom axis). The simulation was run uninterrupted for 48 hours. A simulation of this type would represent turning on the generators without any re-evaluation of wind direction or optimization of timing.

Analysis of the cloud water (green contours) and ice (blue contours) at 1 km MSL, or 0 to +6°C, in Figures 4.14 indicates that ice and snow (not shown here) developed on the extreme northwest slope and the higher peaks of the central section by 15 UTC. By 18 UTC, there was ice and cloud water prevalent along the entire western slope. By 00 UTC on 8 February, the ice cloud had moved to the eastern slope. At 06 UTC, there was ample non-supercooled cloud liquid water present in the east central sections of the range due to the northeasterly flow and strengthening upslope conditions. The cloud water then progressed to the southern tip of the range by 09 UTC. In the simulation, the cloud water started tapering off and ice diminished gradually until around 15 UTC (not shown here). There are greater quantities of cloud water observed near the surface in this region, especially between 03 and 12 UTC on 8 February (lower panels). Qualitatively these results follow the observed trend of more precipitation falling in the southern portions of the region. The trends in both cloud ice and cloud liquid water are similar at 3 km MSL (Figure 4.15). Temperatures at this level range from -2 to –10°C. Therefore, cloud water at this level may be considered supercooled, and the prime target regions for cloud seeding operations. Plots from 18 and 21 UTC on 7 February and 06 and 09 UTC on 8 February show the transition of ice and cloud water concentration from west to east with the changing wind directions.

Tracer Concentration (#)
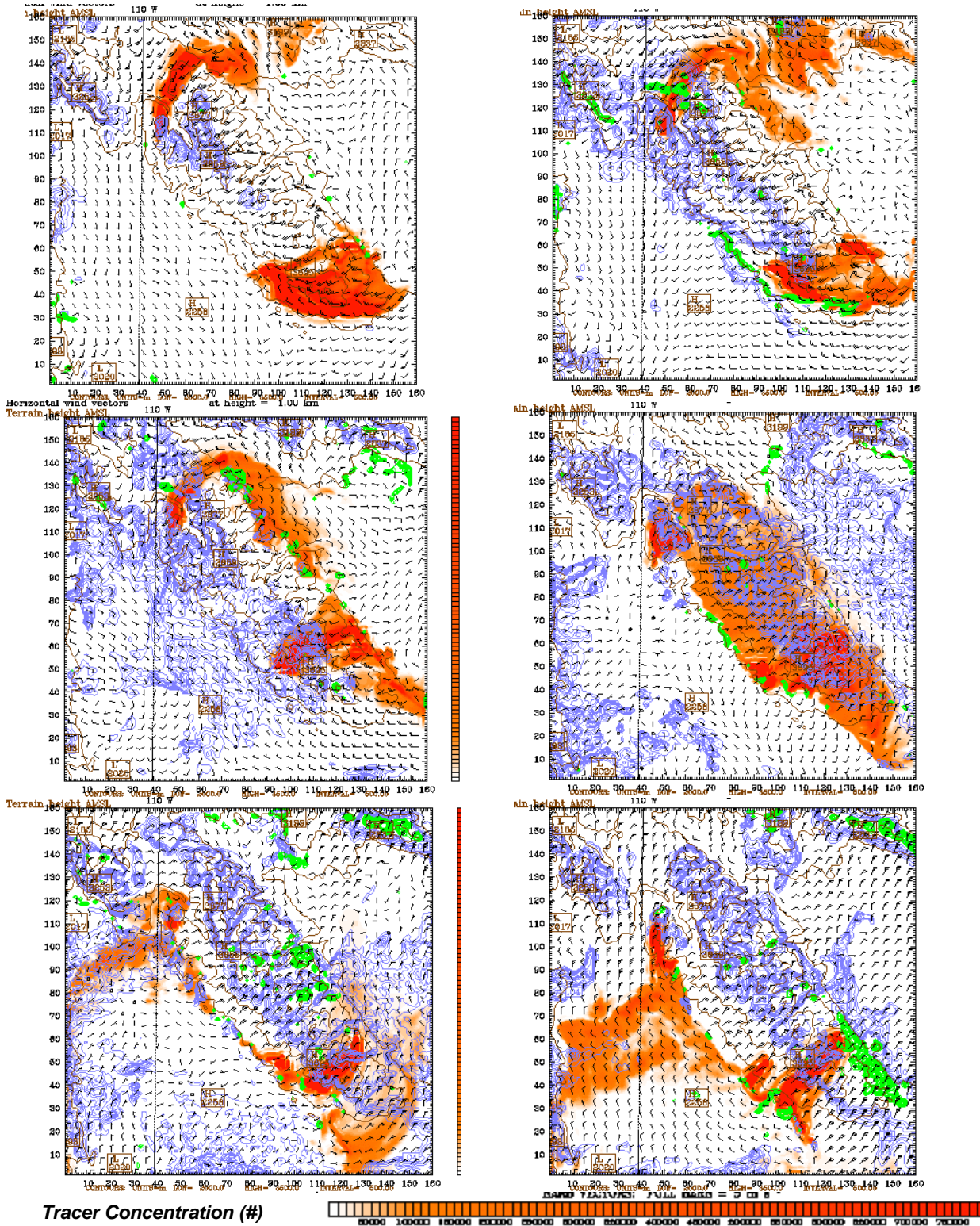
Figure 4.14 - At 1 km MSL, Tracer concentration (orange), cloud water (green contours), and ice (blue contours) at 15 UTC (upper left), 18 UTC (upper right), and 21 UTC on the 7th (middle left) and 00 UTC (middle right), 06 UTC (lower left) and 09 UTC on 8 February (lower right). Contours for both cloud water and ice are from 0.01 to 0.2 g kg^{-1} by 0.005 g kg^{-1}

Tracer Concentration (#)
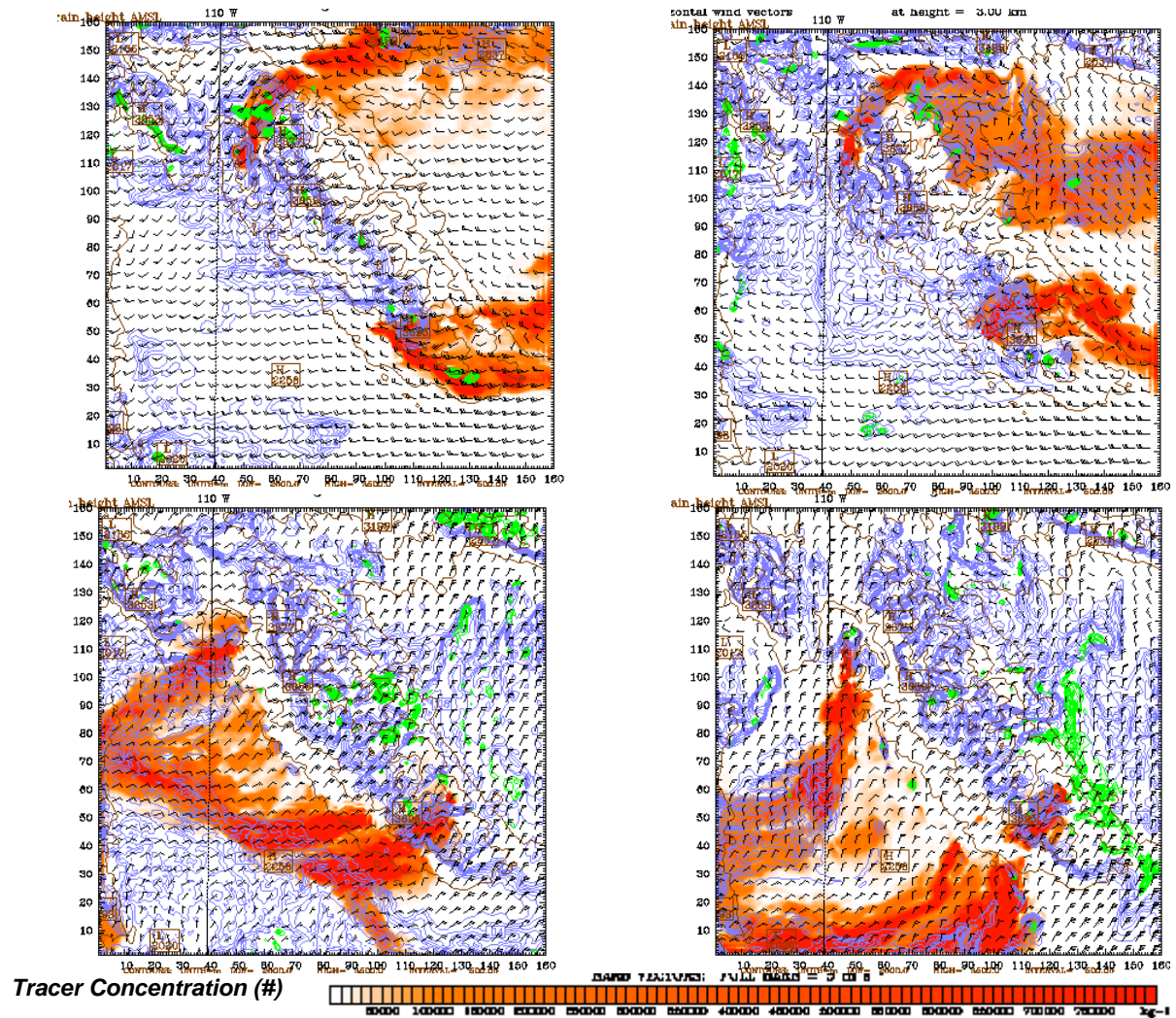
Figure 4.15 - At 3 km MSL, same as Figure 4.14 at 18 UTC (upper left) and 21 UTC on 7 February 2004 (upper right), 06 UTC (lower left) and 09 UTC on 8 February 2004 (lower right). Simulation was initialized at 12 UTC on 7 February 2004. Contour intervals for both cloud water and ice are 0.005 g kg^{-1}. Maximum contour is 0.2 g kg^{-1}

Two plots are shown at 5 km MSL, or -16 to -18°C, in Figure 4.16. The striations perpendicular to the synoptic flow of the ice and cloud water indicates the presence of gravity waves at this level. These waves are induced by flow over a mountain barrier in a stably stratified atmosphere. Clouds, especially cloud water, are found in the rising portions of the gravity wave. Assuming the model has accurately simulated the gravity waves, the cloud water at 5 km provides an excellent opportunity for precipitation enhancement.

Tracer concentration is shown in all three figures through the use of orange filled contours. Dark orange represents concentrations greater than 10^6 kg^{-1}. At 15 UTC on 7 February (Figure 4.14), there is a large concentration of tracer located over the southern tip of the Wind River region. This is due to the placement of one source (or generator) along the western edge, upwind of the steep topography, as well as one source located at higher elevations on the eastern slope. Small quantities of supercooled cloud liquid water are present at 3 km around this time (Figure 4.15).

Tracer Concentration (#)
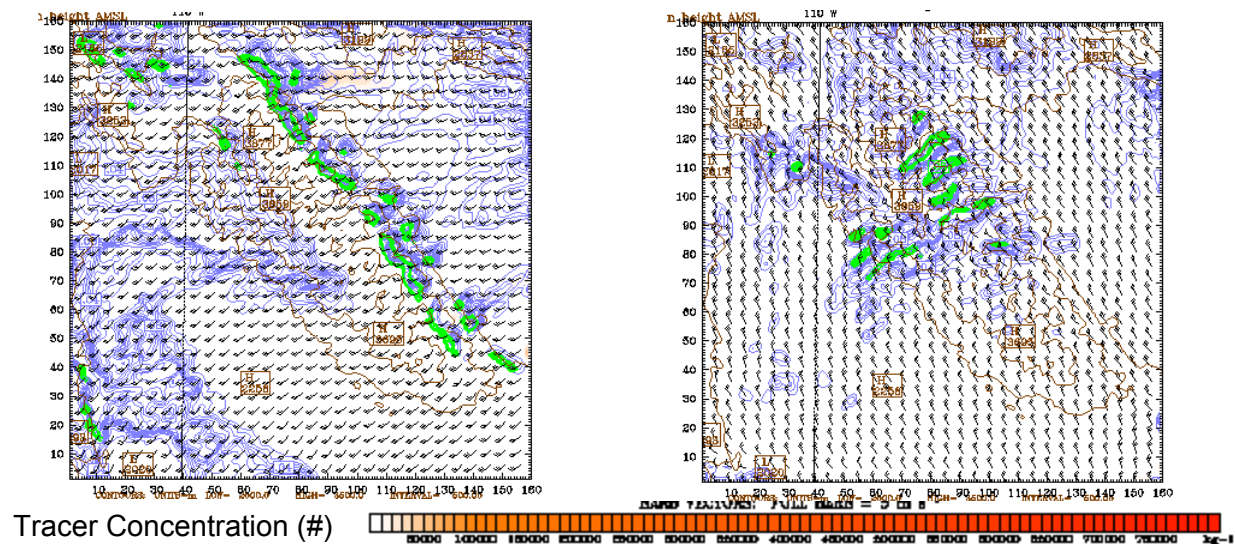
Figure 4.16 - Mixing ratio, at 5 km MSL, of the Tracer (orange fill), cloud water (green contours), and ice (blue contours) at 18 UTC on 7 February 2004 (left), 18 UTC on 8 February 2004 (right). Simulation was initialized at 12 UTC on 7 February 2004. Contour intervals for both cloud water and ice are 0.005 g kg^{-1}. Maximum contour is 0.2 g kg^{-1}

The northern source appears to be providing ample quantities of tracer, hence potential seeding material, at 18 UTC, downstream from Wind River (Figure 4.15), while the southern sources appear to be missing the small regions apparent in the simulation. By 06 UTC, the north-easterly wind flow is driving the tracer to the southwest, away from the regions of cloud water evident in both Figures 4.14 and 4.15. As in Figure 4.12, the tracer tends to be fairly responsive to local wind direction, concentrating in regions based on the flow regime. There does not appear to be much residual tracer left once the winds change direction.

Vertical cross-sections of the same fields shown in Figures 4.14 through 4.16 and along y=100 (oriented east-to-west) and x=100 (north-to-south) are provided in Figure 4.17. The blue contours indicate a fair amount of ice cloud present at both 21 UTC on 7 February (top) and 06 UTC on 8 February (bottom). Cloud water due to upslope flow reaches a maximum mixing ratio of 0.08 g kg^{-1} at 21 UTC on 7 February and 0.12 g kg^{-1} at 06 UTC on 8 February. Cloud water in the gravity waves reach a maximum of 0.2 g kg^{-1} and 0.51 at 21 UTC on 7 February and 06 UTC on 8 February respectively. This suggests that if gravity waves are present they are likely to produce 4 to 5 time more supercooled liquid water (SLW) content then than produced by upslope conditions. This elevated SLW represents another target region for seeding, with the potential to significantly increase the snowfall on the downwind side of the barrier. However, this region will most likely only be reachable via aircraft.

This simulation emphasizes the value of resolving the local wind patterns during seeding activities. The generators were originally implemented to be beneficial in the southwestern flow regime. The upper panels in Figure 4.17 indicate that at 21 UTC the tracer intersects the small amounts of upslope generated cloud liquid water. Mixing is not strong enough to reach the higher level cloud water region. The lower panels indicate the tracer is being mixed higher into the atmosphere with weak concentrations stagnating at mid-levels. They also show that the tracer is on the wrong side of the slope. Had a set of generators been added and activated at

00 UTC, the abundant cloud liquid water, most of which is supercooled, would have been intersected by the tracer.

Tracer Concentration (#)
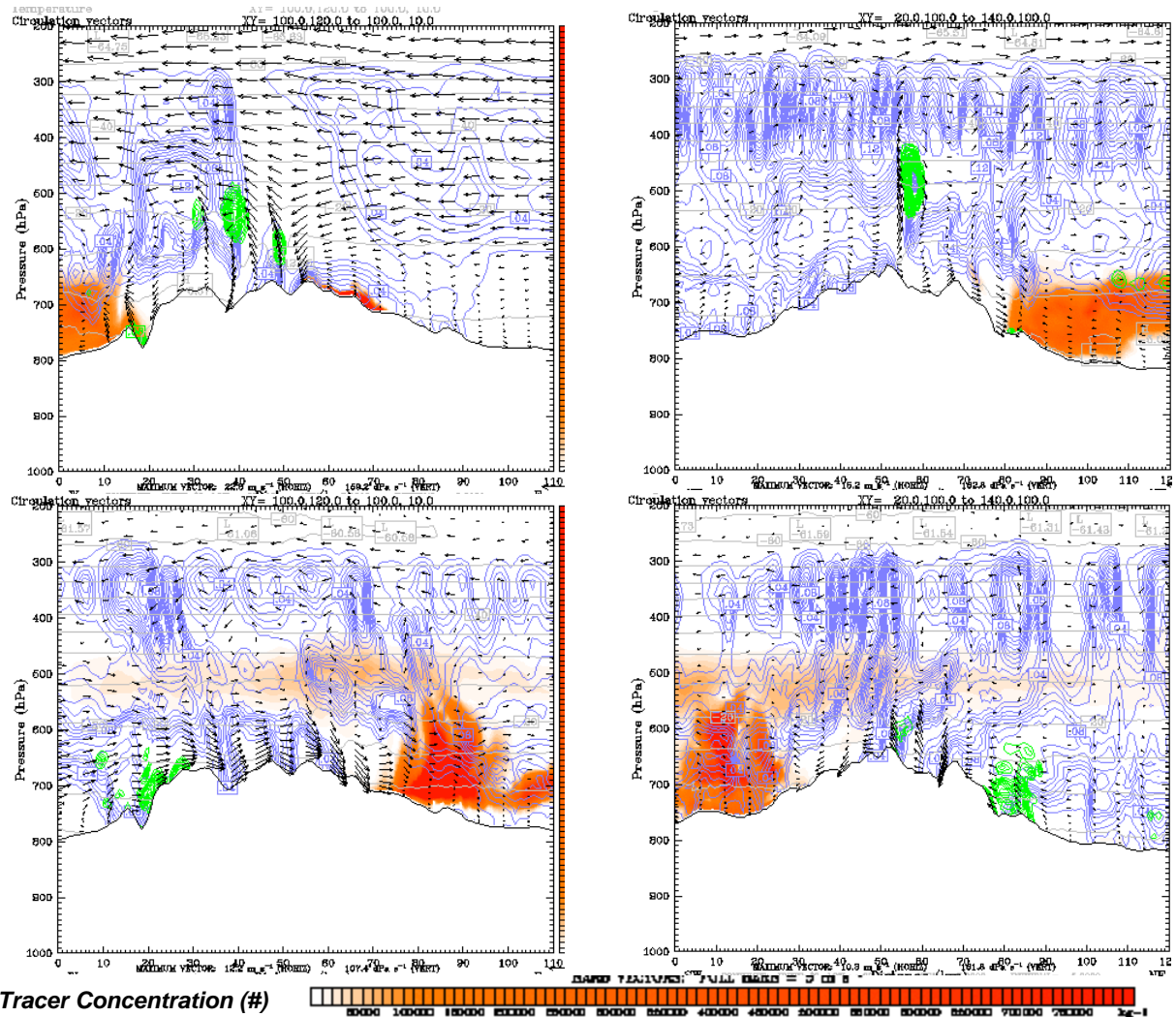
Figure 4.17 - Vertical cross sections of the tracer (orange fill), cloud water (green contours), and ice (blue contours) east-west along grid point 100 at 21 UTC on 7 February 2004 (upper left), north-south along grid point 100 at 21 UTC on 7 February 2004 (upper right), east-west along grid point 100 at 06 UTC on 8 February 2004 (lower left), and north-south along grid point 100 at 06 UTC on 8 February 2004 (lower right). Simulation was initialized at 12 UTC on 7 February 2004. Contour intervals for both cloud water and ice are 0.005 g kg^{-1}. Maximum contour is 0.2 g kg^{-1}

4.7.2   Medicine Bow/Sierra Madre Ranges

A simulation of the Medicine Bow/Sierra Madre region was initialized at 12 UTC on 7 February 2004 with 3 point sources activated at locations 48,40; 45,95; and 85,95 (referred to as Site Configuration 1: from bottom of left axis, from left of bottom axis). This configuration places a source in the southwest quadrant of the Sierra Madre, the southwest quadrant of Medicine Bow, and the north-western edge of Medicine Bow. The model simulation stopped due to numerical instability at 23:46 UTC. A cursory look at the output showed that generator placement had been less than optimal for this dual mountain range. It was decided to "re-site" the generators

to the positions 57, 25; 75, 90; and 90, 97 (referred to as Site Configuration 2). The latter locale was chosen to allow for higher placement of a generator with the possibility of reaching the liquid water regions of the gravity waves. The model stopped again at 21:43 UTC. A brief investigation into the cause of the run-time error revealed no significant reason for the instability. It is speculated that a bug in the model, that has now been fixed, was the cause of this problem.

Results from the first site configuration are presented in Figures 4.18, 4.19 and 4.20. The tracer, cloud water mixing ratio, and ice mixing ratio are shown in a similar manner to those presented for the Wind River case. Figure 4.18 and 4.19 shows that the general wind direction was south-westerly but did not produce any noticeable cloud water or ice at 1 km and 3 km until 21 UTC (lower panel). The cloud water and ice mixing ratios indicate the cloud developed along the western slope of the Sierra Madres and northern sections of the Medicine Bow range. The tracer only intersects a few small patches of the cloud liquid water, suggesting the generator for this situation should have been further north along the range. Vertical mixing finally elevated significant amounts of tracer up to the SLW level (3 km) by 21 UTC. However, the tracer is east of the primary liquid water regions at this level.

Tracer Concentration (#)
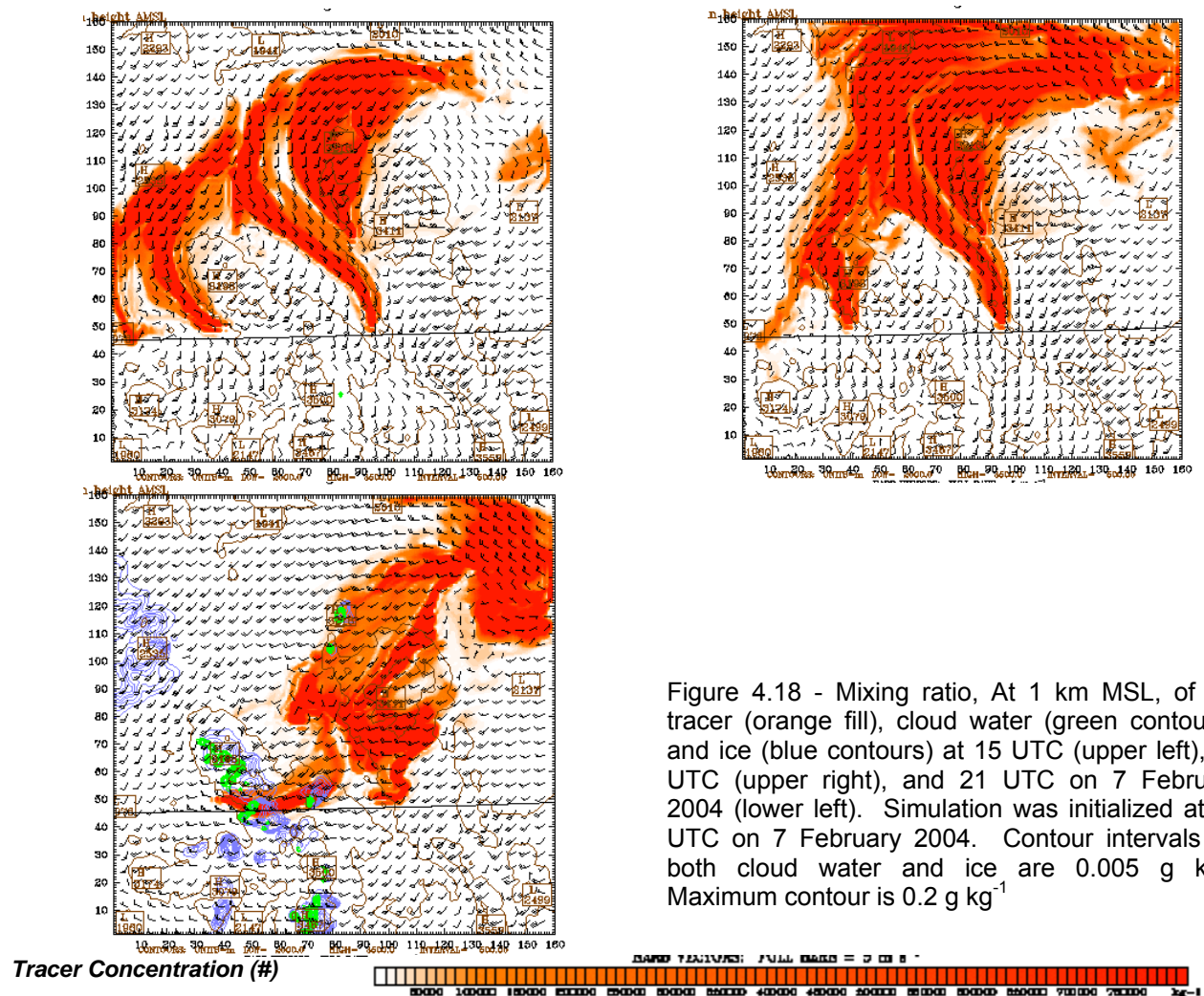
Figure 4.18 - Mixing ratio, At 1 km MSL, of the tracer (orange fill), cloud water (green contours), and ice (blue contours) at 15 UTC (upper left), 18 UTC (upper right), and 21 UTC on 7 February 2004 (lower left). Simulation was initialized at 12 UTC on 7 February 2004. Contour intervals for both cloud water and ice are 0.005 g kg^{-1}. Maximum contour is 0.2 g kg^{-1}
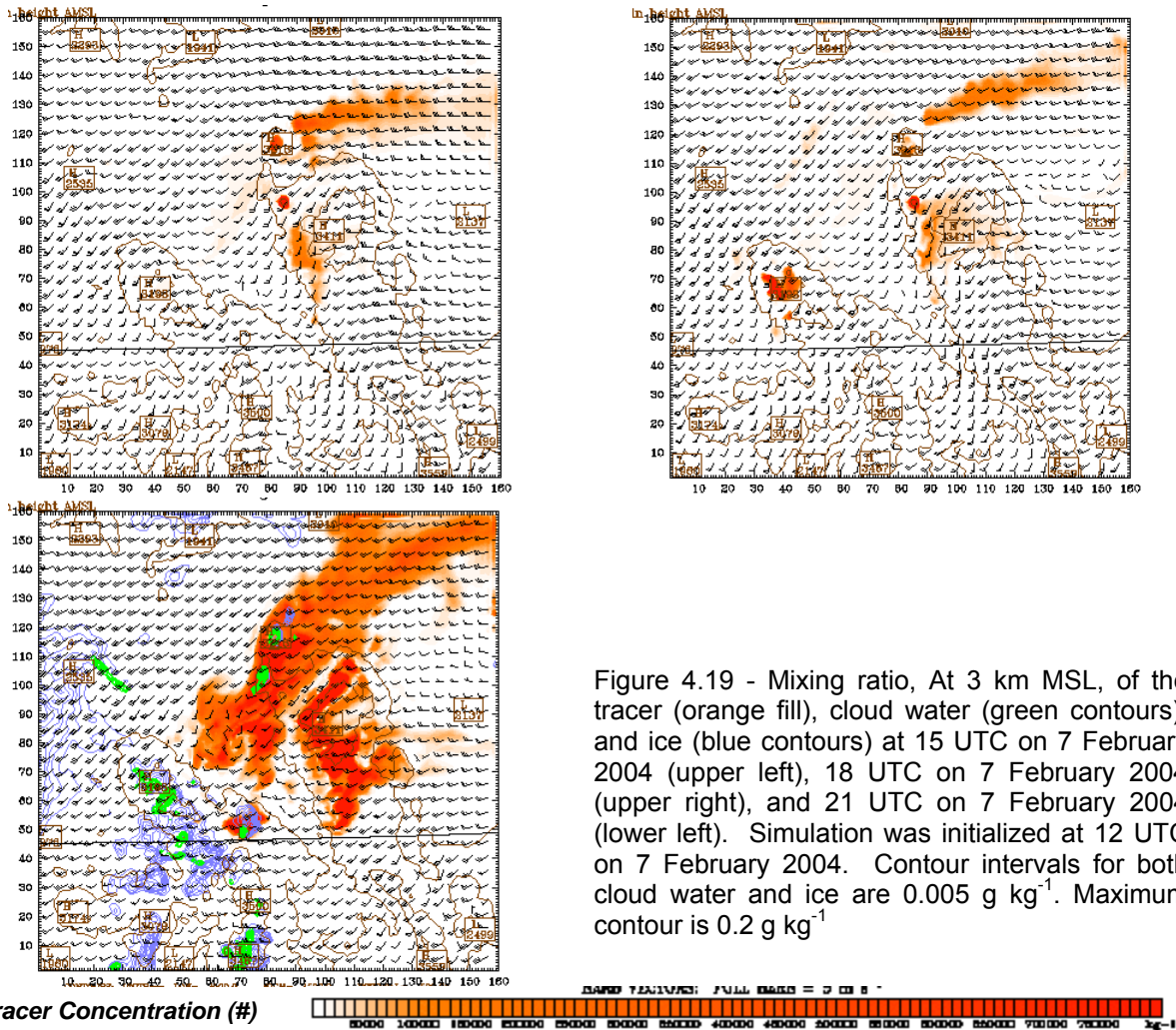
Figure 4.19 - Mixing ratio, At 3 km MSL, of the tracer (orange fill), cloud water (green contours), and ice (blue contours) at 15 UTC on 7 February 2004 (upper left), 18 UTC on 7 February 2004 (upper right), and 21 UTC on 7 February 2004 (lower left). Simulation was initialized at 12 UTC on 7 February 2004. Contour intervals for both cloud water and ice are 0.005 g kg^{-1}. Maximum contour is 0.2 g kg^{-1}

Tracer Concentration (#)

Ice and cloud water mixing ratios indicate the presence of gravity waves at 5 km (Figure 4.20) during this simulation. This is also similar to the Wind River case. Further investigation of the existence of these gravity waves will need to be conducted before these results are considered conclusive. As stated previously, the presence of the gravity waves at 5 km and the poor selection of point source placement led to a modification in the site configuration. The Sierra Madre generator was moved further north and west along the range to target the upslope cloud water and the southern most Medicine Bow generator was moved to a peak to try and target the north-eastern upslope and gravity wave SLW regions.

Figure 4.21 provides the same fields at 1, 3, and 5 km at 21 UTC using the second site configuration. There appears to be a slight improvement in the intersection between tracer and SLW with the re-siting. The tracer from the Sierra Madre source, at 1 km, intersects the majority of cloud water within Wyoming. However, this tracer only intersects the supercooled water approximately 50 km downwind of the generator. This suggests the source may need to be placed further upwind to give ample time for the tracer to be mixed vertically to reach the SLW. The other interesting feature is the presence of a very weak tracer signature at 5 km over the central region of Medicine Bows. This suggests that strategically placed generators at higher elevations may be able to tap into the lower portion of the gravity wave induced SLW. This idea is supported by the vertical cross-sections shown in Figure 4.22. Both cross sections taken

through the simulation using Site Configuration 1 indicate the tracer is not being horizontally advected into regions of stronger vertical motion. Hence, the tracer does not reach the cloud water region at higher levels. The same cross sections taken through the simulation using Site Configuration 2 show a significantly greater amount of tracer reaching bottom edge of the higher SLW region.

It should be noted that the maximum cloud water mixing ratio induced by gravity waves ranged from 0.2 to 0.43 g kg^{-1} while the cloud water generated by upslope only reached a maximum of 0.056 g kg^{-1}. If these results prove consistent with observations, the higher cloud regions may have 7 to 8 times more SLW than is found in upslope conditions. The fact that the tracer barely reaches these elevated SLW regions is one reason that airborne seeding should be considered a necessary part of the project design.
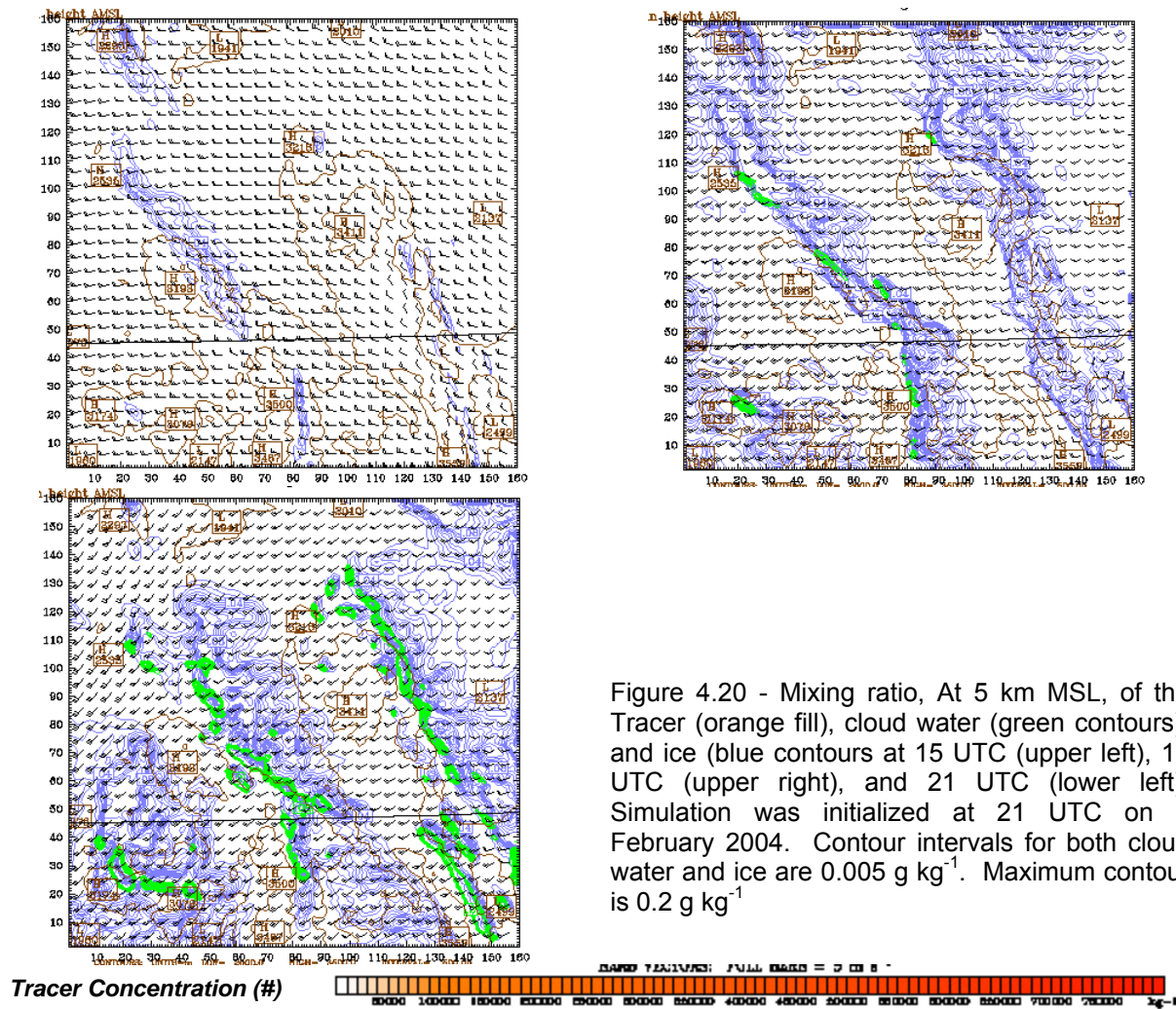
Figure 4.20 - Mixing ratio, At 5 km MSL, of the Tracer (orange fill), cloud water (green contours), and ice (blue contours at 15 UTC (upper left), 18 UTC (upper right), and 21 UTC (lower left). Simulation was initialized at 21 UTC on 7 February 2004. Contour intervals for both cloud water and ice are 0.005 g kg^{-1}. Maximum contour is 0.2 g kg^{-1}

Tracer Concentration (#)
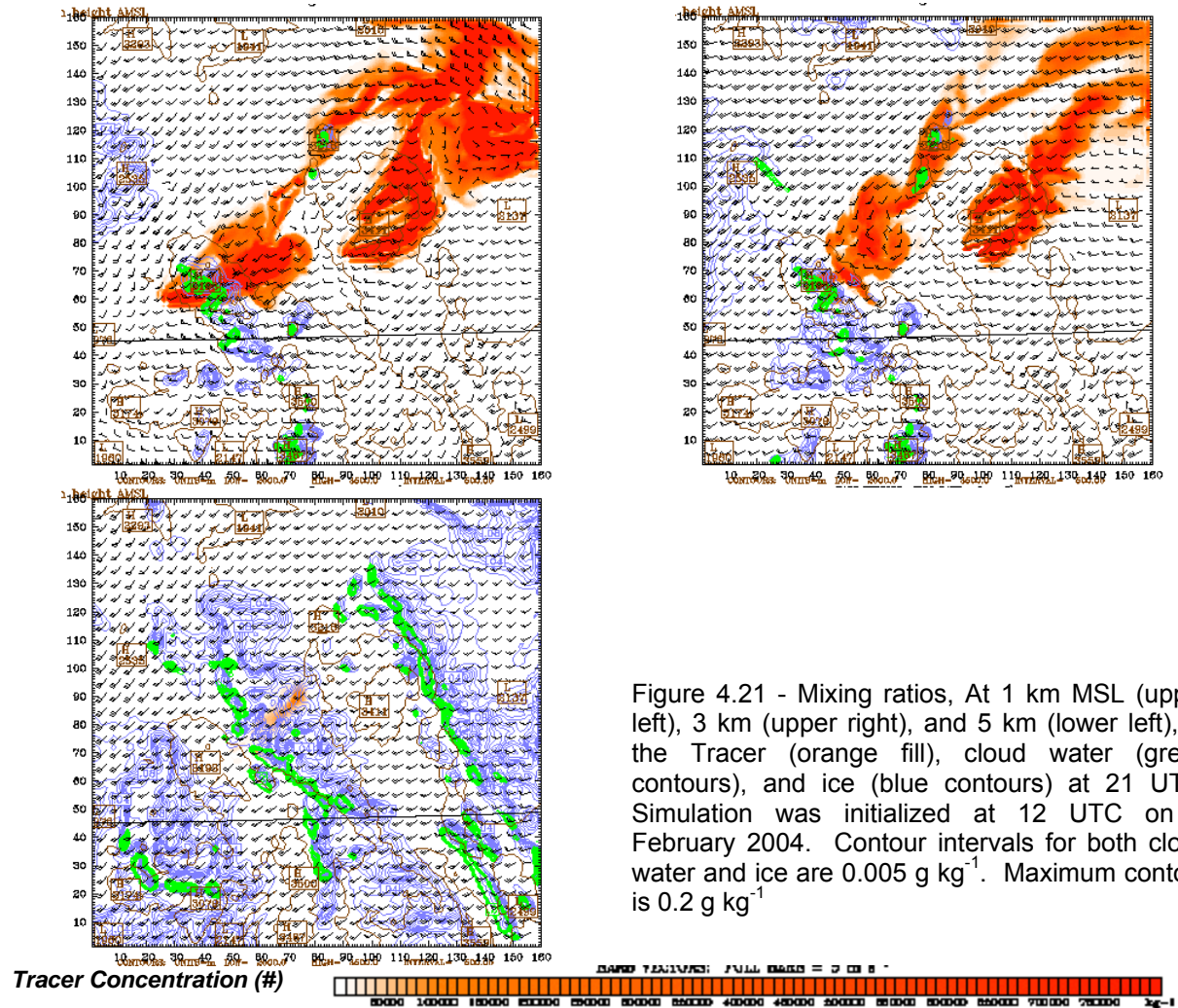
Figure 4.21 - Mixing ratios, At 1 km MSL (upper left), 3 km (upper right), and 5 km (lower left), of the Tracer (orange fill), cloud water (green contours), and ice (blue contours) at 21 UTC. Simulation was initialized at 12 UTC on 7 February 2004. Contour intervals for both cloud water and ice are 0.005 g kg^{-1}. Maximum contour is 0.2 g kg^{-1}

Tracer Concentration (#)

4.8   Summary and Implications for Project Design

The modeling results can be summarized as follows:

1. As expected during the passage of a winter storm, the wind flow patterns and associated liquid water content regions shows rapid temporal and spatial changes depending on the evolving features of the system (Figure 4.14). This has also been observed in numerous other winter orographic cloud seeding experiments in the western U.S.

2. The tracer/seeding material released on the upwind side of the mountain barriers from a single generator initially spreads to a plume of approximately 10 km wide for a distance of approximately 10 km away from the generator with a rate of 1km horizontal spread for every 1km distance away from the generator. After 10km the rate of spread decreased somewhat. These results are consistent with those reported from observations in the Medicine Bow mountain range by Auer et al. (1970).

3. The vertical extent of the plume remained less than approximately 500 m above the terrain level and follows the slope of the mountain and sinks again the lee of the mountain. However, once in the lee of the mountain, the material is lifted into some of the lower gravity waves that are excited by the topography. These results are also consistent with observations reported in Auer et al. (1970).
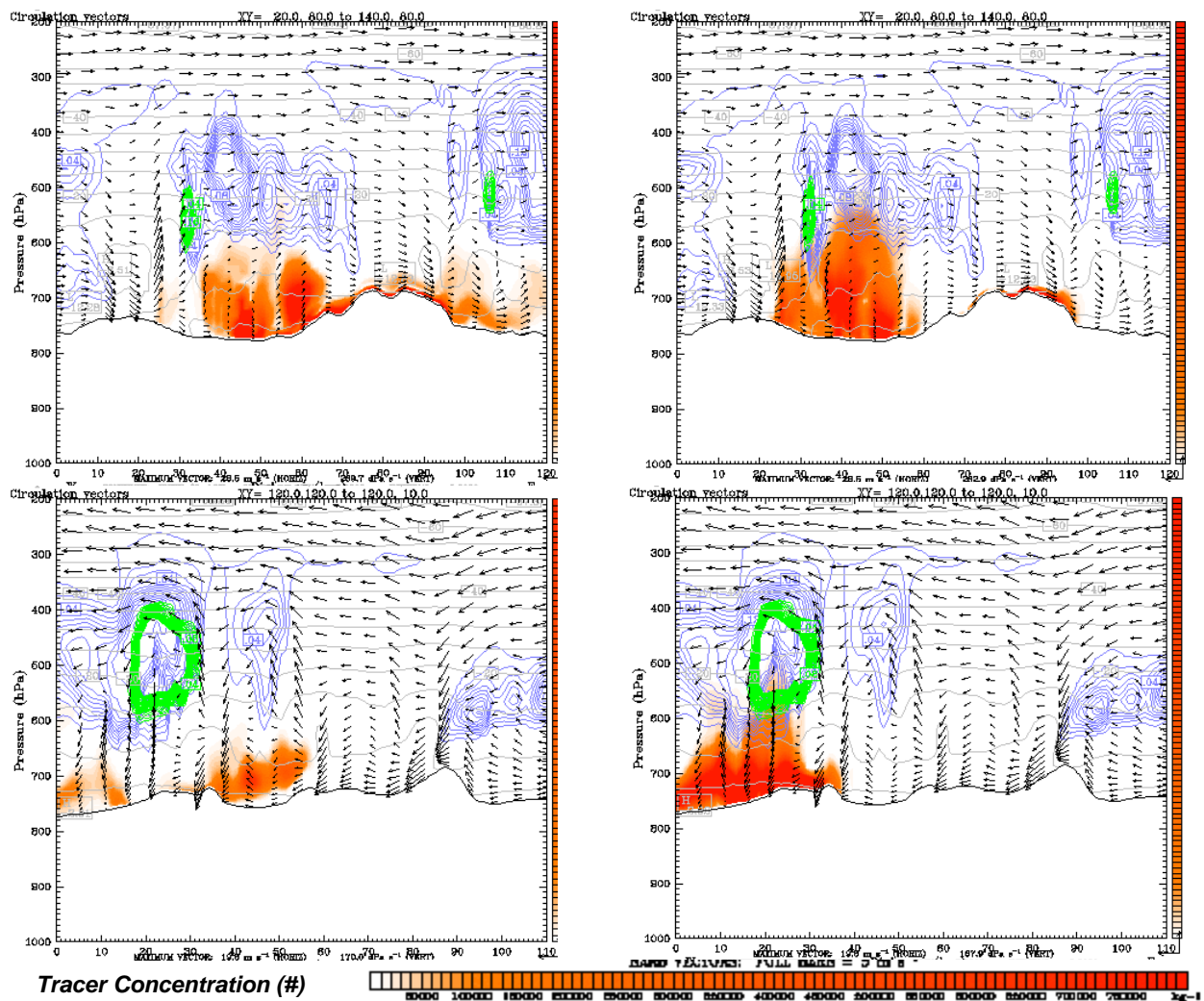
Figure 4.22 - East-West Vertical Cross Section (through center of grid), at 21 UTC on 7 February 2004, for siting configuration 1 (left) and siting configuration 2 (right). North-South Vertical Cross Section (through grid line 120 of 160), for siting configuration 1 (left) and siting configuration 2 (right). Mixing ratios, of the Tracer (orange fill), cloud water (green contours), and ice (blue contours) at 12 UTC. Simulation was initialized at 12 UTC on 7 February 2004. Contour intervals for both cloud water and ice are 0.005 g kg^{-1}. Maximum contour is 0.2 g kg^{-1}

4. SLW associated with the forced lifting of the air over the topography is strongly linked to the upwind side of the mountain and the amount of supercooled water available for seeding is tied to the strength of the cross-barrier wind component.

5. Depending on the cross-barrier wind component and moisture availability these liquid water content regions can occur up to about 1 km above the terrain (excluding gravity waves).

6. Gravity waves and associated liquid water content regions were evident in all the simulations and were forming in lines in the lee of the mountain peaks orthogonal to the wind direction. These gravity waves contained substantially larger amounts (5 to 10 times) of SLW than the upslope SLW regions. This is very similar to the results found in observational and modeling studies in northern Arizona (Bruintjes et al. 1994).

The implications for the design of cloud seeding experiments are as follows:

1. Ground-based generators should be used to target the SLW regions associated with forced lifting over the mountains. However, in the absence of convection, seeding with ground-based generators will only have an affect on the SLW regions in approximately the lowest 500 m above the terrain. Seeding with aircraft in these regions will also be impossible because of safety concerns and minimum altitude flight restrictions. A coordinated effort using both ground-based and airborne seeding would maximize the benefits of seeding.

2. In order to target the SLW above 500 m AGL, and in the gravity waves, aircraft will be the only option. However, because of the temporal and spatial variability of these waves, one aircraft could possibly be used to target both ranges as the weather system traverses the region.

3. Indiscriminate seeding with generators by leaving them on throughout entire winter storm periods, with no regard for wind direction and thermodynamic structure of the atmosphere would result in a large amount of seeding material being wasted, and in the absence of cloud, could result in seeding agent traveling considerably beyond the intended target areas.

4. Real-time high resolution (4 km grid spacing or less) numerical model simulations are essential for determining wind-flow and SLW regions and should be used for both temporal and spatial guidance in operating seeding generators and aircraft operations.

5. Although upper air winds in the region are mostly from the northwest to southwest, surface wind directions can also occur from the east depending on the evolution of the weather system that traverses the region. This means that seeding generators should be located on both sides of the mountain ranges to capture all the precipitation events.

6. Based on the modeling results the generators should be located approximately 15 to 20 km upwind of the target area and spaced at about 30 km intervals.

4.9 Preliminary Project Design

Based on the results presented in this section, it is recommended that the operational program for both ranges incorporate the following units:

1. Ground-based generators should be located approximately 15 to 20 km upwind of the target area and spaced at about 30 km intervals. It is also recommended that generators should be located on both sides on the mountain ranges to capture all upslope snowfall events. Figure 4.23 provides a conceptual model of where these might be placed.

2. Aircraft should be used for seeding SLW cloud regions above 500 m AGL, embedded convective cloud turrets, gravity waves, and where ground-based generators cannot be appropriately deployed, such as wilderness areas.

3. All current observational tools should be used for daily briefings to evaluate seeding potential.

4. Real-time high resolution (4 km grid spacing or less) numerical model simulations should be used for both temporal and spatial guidance in operating seeding generators and aircraft operations.

4.9.1   Seeding Equipment and Aircraft

For the past 40 years, numerous winter orographic cloud seeding programs with the goal of augmenting the amount of snowfall on mountainous terrain for additional water resources or additional snow for ski resorts have been conducted. Usually, a network of generators upwind from the target release silver iodide particles or liquid propane to enhance ice crystal growth. Aircraft have been used less often than ground generators for seeding due to the inherent hazards of flying aircraft missions in mountainous terrain during the winter. However, with a powerful aircraft and properly trained crew, the use of airborne seeding techniques will be very beneficial to an operational program.

The model simulations in this section indicate that ground-based seeding generators should be spaced approximately at 30 km intervals to be able for the seeding material to reach regions of supercooled liquid water content and somewhat overlap with each other. This would mean that approximately 12 to 14 seeding generators would be needed for each of the Wind River Mountain Range and the Medicine Bow/Sierra Madre Mountain Range target areas.   It is recommended that these generators be remotely-controlled units due to their quick response capability and versatility in siting options.   Table 4.6 highlights the advantages and disadvantages of using remotely-controlled versus manually-controlled generators.

Table 4.6 – Comparison of Advantages and Disadvantages of Remotely-Controlled and Manually-Controlled Ground-Based Ice Nuclei Generators.

Factor	Remote Control	Manual Control
Cost of Unit	Relatively expensive. Requires telemetry system for control, on-site power source, sensors to confirm unit is performing.	Inexpensive. Turn-on and shut down is done by humans. Most manual generators have no provisions to relay or record any performance data.
Cost of Operation	Primary cost is in deployment and, when necessary, servicing.	Project personnel are required to visit each site each time each unit is turned on or turned off. Generators often run longer than necessary, and may not be turned on until well after opportunities are first recognized.
Response Time	One minute or less.	Depends upon the number of project staff available to run the generators. It may take hours for a team of several persons to visit each site and turn each on or off. Exception is if unit is sited at location staffed 24/7.
Siting Consider-ations	Can be sited virtually anywhere, even in rugged, high terrain, where transport of seeding agent to target is ensured. Control is by means of satellite telephone, so cell-phone coverage is not an issue.	Must be placed in readily accessible sites in order to reduce response time. In most cases, this precludes siting the generators in higher altitudes unless an all-weather road is nearby. Should not be sited in low elevations (below valley inversions) unless nearby terrain is very gently sloped, as is the case on the southern end of the Wind River Range where the Eden Valley Irrigation District operates.
Weather & Generator Data	Can readily be included in data telemetry. Common parameters include temperature, wind vector, humidity, flame temperature, and seeding solution flow rate.	Meteorological instrumentation can be included with manual units, but seldom is. If it is, real-time data access is not available.

The *approximate* suggested locations of the ground-based seeding generators for the Wind River and Medicine Bow Mountain Ranges are shown in Figure 4.23. Exact siting of the generators will need to occur well prior to the start of the project, so that appropriate approvals can be obtained. Section 7 provides details on permitting requirements and legal aspects of this process.
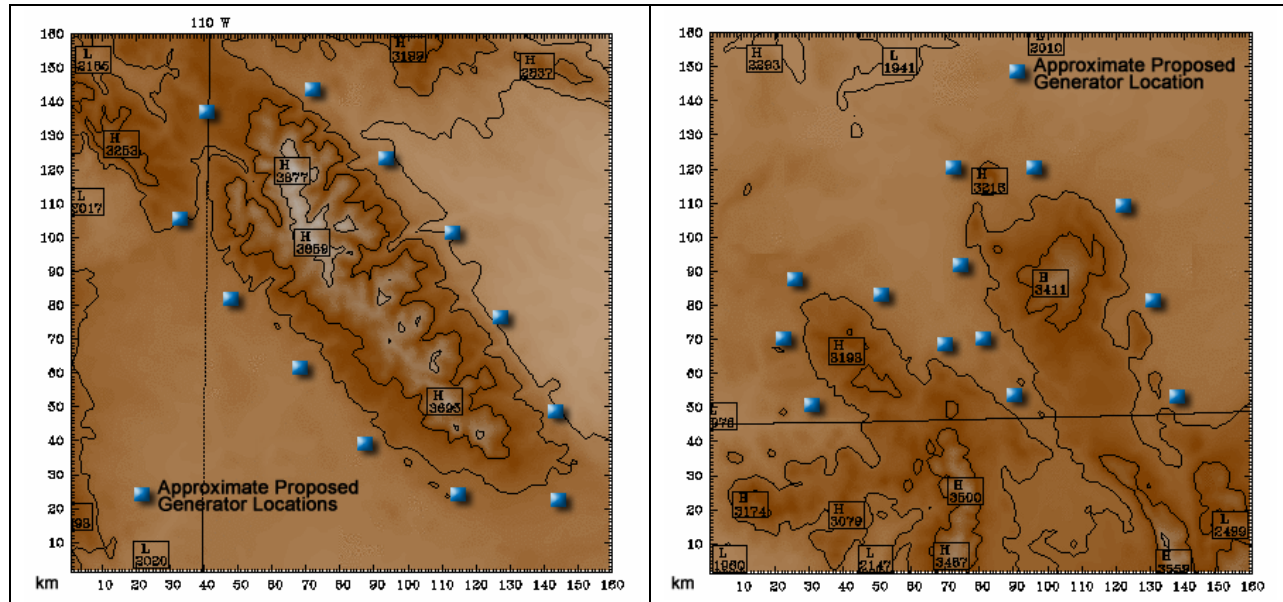
Figure 4.23 - Suggested locations of generators for Wind River (left) and Medicine Bow/Sierra Madre Mountain ranges (right). Axes are in kilometers.

The aircraft should be equipped with wing racks and belly racks for silver iodide flares. In addition, it should be equipped with a basic instrument package that includes temperature, pressure, humidity, and a telemetry system that indicates the position of the aircraft. If possible a liquid water content sensor would also be highly desirable for airborne cloud liquid water content measurements. These data should be recorded on a data system at least once per second. The aircraft should be certified to fly in known icing conditions because this is where most of the airborne seeding will be conducted. Additional uses and instrumentation for the evaluation of the program are described in Section 9.

Much has been learned through the UW research at Elk Mountain. The primary conclusion to be drawn from this research is that many orographic clouds develop and persist over Wyoming Mountains for extended periods during the winter months, often without significant precipitation. These cap clouds contain significant amounts of SLW that, if frozen by artificial means (cloud seeding) could readily grow to precipitation sizes and be made to contribute to the snowpack. If not converted to ice naturally, this SLW is transported by the wind flow to the lee side of the mountains, where the air descends and warms, evaporating the cloud. It is thus possible to convert this unprecipitated water to ice through seeding, thus augmenting the mountain snowpack. Over the course of a winter season, evidence suggests that natural precipitation could be increased by a minimum of ten percent, and perhaps more than twenty percent. The UW research eventually led to the design and implementation of an operational cloud seeding program for the Eden Valley Irrigation District (Farson), which is still in operation today. The proposed project should incorporate the existing Eden Valley seeding facilities, located on the gentle slopes of the southern end of the Wind River Mountains, in its final design.

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4.9.2   Observational Tools

An Operations Center will have to be established for the cloud seeding program. This could possibly be located near one of the current NWS offices in the State, or possibly at WWDC offices in Cheyenne. The Operations Center should consist of an office with communications for access to the data described in the previous section. In addition, the activation (either by remote control or manual by telephone) and the dispatch of the aircraft should occur from this Center.

Access to the following observational data at the Operations Center would be essential for the conduct of the program:
   1. Riverton and Cheyenne WSR-88D radar data
   2. Precipitation and SNOTEL data from Medicine Bow/Sierra Madre and Wind River Mountain Ranges
   3. Riverton Rawinsonde data
   4. Medicine Bow Wind profiler data
   5. Synoptic data and maps
   6. Satellite imagery of cloud systems
   7. Pilot Reports, especially those noting aircraft icing

It is important to note that these observational tools are already available and use the current infrastructure available in Wyoming (see Figure 4.24).
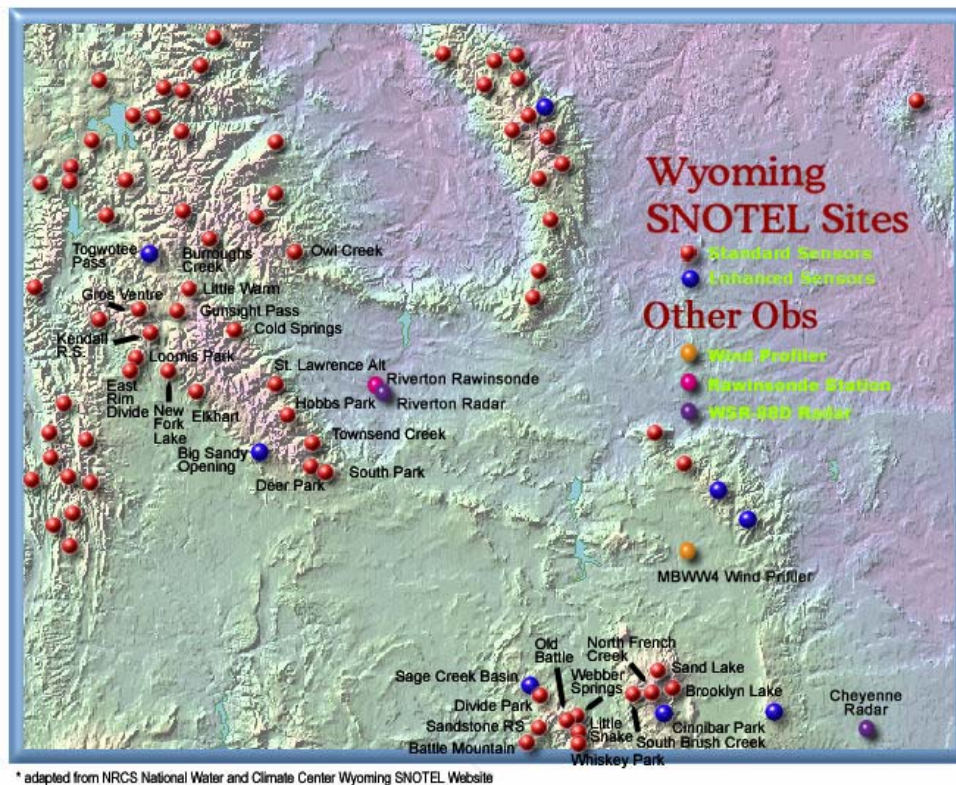
Figure 4.24 - Observation locations, including SNOTEL, radar, rawinsonde, and wind profilers available in Wyoming.

4.9.3 Numerical Model Predictions

Historically, forecast guidance for these programs has primarily come from weather services products, which provide large scale flow pattern information typically resolved no better than 80km in the horizontal. Other data accessible to the forecaster consisted of local sensor networks which provided data in near real-time. Based on the previous experience of using high-resolution, time dependent numerical models to guide cloud seeding experiments discussed in the previous section, we suggest that either the WRF or NCAR/Penn State MM5 Real-Time numerical models with Four Dimensional Data Assimilation be run at least once a day (and possibly twice a day) to provide the initial guidance for the experiment. It is anticipated that the model should be able to provide information about the alignment of the upslope clouds, cloud bands, SLW regions and their temporal evolution. These simulations should also indicate the regions of updrafts and potential cloud liquid water regions that should be targeted by either the ground-based generators or the seeding aircraft.

These model simulations could be conducted on a cluster of Personal Computers (PC's; Figure 4.25) either at a research institution (e.g., NCAR, or the University of Wyoming) or a local NWS office, and have the model predictions disseminated via the web to different users including the Operations Center. A new cluster of PC's that would be sufficient for the real-time model runs costs approximately US$150,000. The cost for the implementation and maintenance of the model simulations for the duration of the experiment should be approximately US$50,000 per season.

Figure 4.25 - Example of a PC "cluster" for numerical model simulations.

The objective of the model predictions would be to characterize the wind-flow patterns, cloud structures and associated cloud liquid water regions and precipitation. The following information should be obtained from the model predictions:
1. Structure of clouds (e.g. upslope clouds, cloud bands and/or patches)

2. Alignment of wind flow, upslope clouds, cloud bands and/or patches
3. Movement and speed of the cloud band and/or patches of clouds with changing wind flow patterns
4. Radar echo structures predicted by the model
5. Cloud liquid water content regions predicted by the model
6. Approximate time that upslope clouds, cloud bands and/or patches will enter the Medicine Bow-Sierra Madre and Wind River Mountain region

Initial generator activation and flight patterns should be developed based on the above information provided by the numerical model simulations. The model predictions should subsequently be verified by the Cheyenne and Riverton WSR-88D radar data as the cloud systems approach either the Medicine Bow/Sierra Madre or the Wind River Mountain Ranges. To the extent possible given the limitations of WSR-88D radars to detect drizzle and light snow, and terrain blockages, the following information should be obtained from the radar data:

1. Structure of echoes (e.g. bands and/or areas) and relation to the model predictions.
2. Alignment snow or precipitation echo bands and/or areas
3. Movement and speed of the band and/or areas of echoes
4. Approximate time that the bands and/or areas will enter the Medicine Bow/Sierra Madre and Wind River seeding areas

The model predictions of precipitation in the region should also be compared to the SNOTEL data to validate the model predictions and to adapt seeding strategies. The following parameters are important to validate:

1. Onset time of precipitation
2. Phase of precipitation (e.g. liquid or ice)
3. Rate of precipitation
4. Accumulated precipitation

The model-simulated winds should be further validated by Riverton Rawinsonde (RIW) and the Medicine Bow (MBWW4) wind-profiler data in order to possibly detect model biases in a similar manner as with the radar and surface observations. These comparisons could be conducted in real-time. Any biases should then be included in operational decisions to activate the ground-based generators and launch the aircraft. An Operations Plan should be developed before any cloud seeding program that would include the procedures, specifics and criteria for activation of the ground-based seeding generators and /or aircraft. Details of the criteria for activation and procedures will be further discussed in Section 5.

Another numerical tool that is currently available on the web for the Sierra Madre/Medicine Bow regions is the Snow Data Assimilation System (SNODAS) provided by the National Operational Hydrologic Remote Sensing Center (NOHRSC). This model is a distributed, energy-and-mass-balance snow model and data assimilation system designed to augment basic hydrological analysis. The model is driven by a down-scaled analysis and forecast fields from a mesoscale forecast model, such as ETA or RUC2, surface weather observations, satellite derived solar radiation data, and radar derived precipitation products. SNODAS provides near real-time analysis and forecasts of snow characteristics including: snow water equivalent, and snow depth change. Products are posted to the web at: http://www.usbr.gov/pmts/rivers/awards/SNODAS/SNODAS_CO_hist.html for the region of north eastern Colorado, but includes the Medicine Bow/Sierra Madre ranges in Wyoming.

Therefore, it is important that the WSR-88D radar, wind-profiler and the surface data be available in real-time at the Operations Center of any future cloud seeding program. An Operations Director should be able to have access to these data and the model results to continuously monitor the situation.

5.   ESTABLISHMENT OF OPERATIONAL CRITERIA

5.1   General Overview

A seeding operation is initiated when the forecast calls for clouds containing supercooled liquid water to be passing over the target area (as determined by high-resolution numerical model simulations). Under these conditions, the generators that line up with the direction of the large-scale wind flow are fired up, and an aircraft is launched if SLW is predicted at altitudes that cannot be adequately targeted by the ground-based generators and/or in regions not treatable by ground-based generators, e.g. portions of wilderness areas. The objective is to intercept the desirable clouds with plumes of silver iodide-complex glaciogenic seeding agent. It is critical to properly time the releases and correctly select which generators to activate in order for the plume-cloud intercept to occur. In the case of aircraft operations, the Operations Director should advise the flight crew of the probable locations of SLW-laden clouds, especially those at altitudes or locations not treatable by ground-based seeding, including convective cloud turrets.

Previously in glaciogenic seeding programs, forecast guidance has primarily come from Weather Service products, which provides large scale flow pattern information typically resolved no better than 80 km in the horizontal. Based on previous experiments, the time and spatial resolutions of these forecast tools is not sufficient to properly aid in operational procedures on a given day. Results from Section 4 indicate using high-resolution numerical models to guide cloud seeding experiments is necessary to correctly decide which generators to activate. We suggest that either the WRF or NCAR/Penn State MM5 Real-Time with Four Dimensional Data Assimilation numerical models be run at least once a day to provide the initial guidance for the project. Initial generator activation and flight patterns will be developed based on the above information provided by the numerical model simulations. Subsequent modifications to the activation criteria would also be aided by the use of the mesoscale model predictions.

It is also important that during any cloud seeding program the WSR-88D radar, rawinsonde, wind-profiler and the surface data be available in real-time or near-real-time at the Operations Center. In addition, synoptic data and satellite imagery should be available to qualitatively evaluate the model predictions of synoptic and cloud systems.

5.2   Operational Procedures

It is suggested that a daily briefing be held in the morning at the Operations Center. All staff will be participating in the briefing either on-site or via telephone conferencing. The briefing will consist of the following parts:
  – Debriefing of previous day's forecast and operational activities
  – Review of snowpack information from SNOTEL sites
  – Forecast for the day and outlook for the following two days
  – Review of equipment and data archival status
  – Operational plans
  – Schedule for the day

When operational, all active crew members will remain on alert until officially called down by Operations Director or a designated representative. Crew members uncertain of their status will contact the Operations Director for clarification. Apart from operations periods, the normal working day hours will be from 9:00 AM to 6:00 PM. During seeding operations or when seedable weather is anticipated, crews will operate for as long as seeding opportunities exist.

5.2.1 Operational Status and Launch Decisions

The Operations Director will call for the generators to be activated and the aircraft to launch when model forecasts, visual observations, radar echoes and/or nowcast conditions suggest a reasonable likelihood of finding suitable clouds. In addition, the Operations Director will also decide when to terminate generator and airborne operations when seeding will no longer be effective (see When Not to Seed).

On standby days, equipment will be kept in a state of readiness for operations.

On no-go days, maintenance and other activities that will affect the operational readiness of the equipment may be carried out.

The Operations Director will determine days for crew rest and will attempt to schedule these preferably on clear days. After intensive operations periods, crew rest should be scheduled if possible.

During the daily weather briefing, a preliminary plan should be developed for which generators to activate and at what time. In addition, a preliminary decision will be made when to launch the aircraft and a preliminary flight plan designed.

5.2.2 Ground-Based Seeding Procedure

Silver Iodide generators should be turned on at the prescribed time, based on the daily forecast. Activation time should be approximately 30 minutes prior to the onset of expected optimal conditions. Generator output rates can be varied, but at least initially should be 30 g AgI consumed per hour. Varying the seeding rates would introduce yet another variable into an already complex system, and complicate evaluation efforts.

After activation occurs, there should be constant monitoring of mesoscale wind conditions through the use of observations and forecast models to determine if seeding should continue. Ground-based seeding should cease when upslope conditions weaken to the point of no longer providing sufficient lift to produce clouds.

5.2.3 Aircraft Based Seeding Procedure

There are several options for airborne seeding flight patterns.

Cloud Bands. In the case of cloud bands associated with fronts or other synoptic-scale features, the initial flight pattern will be conducted according to the flight pattern shown in Figure 5.1, and measurements will be coordinated according to the following schedule as guided to the extent possible by the Operations Director:

1. After take-off the aircraft will proceed to the center of leading edge of the cloud band (associated with upslope or gravity wave) that will enter the target region.
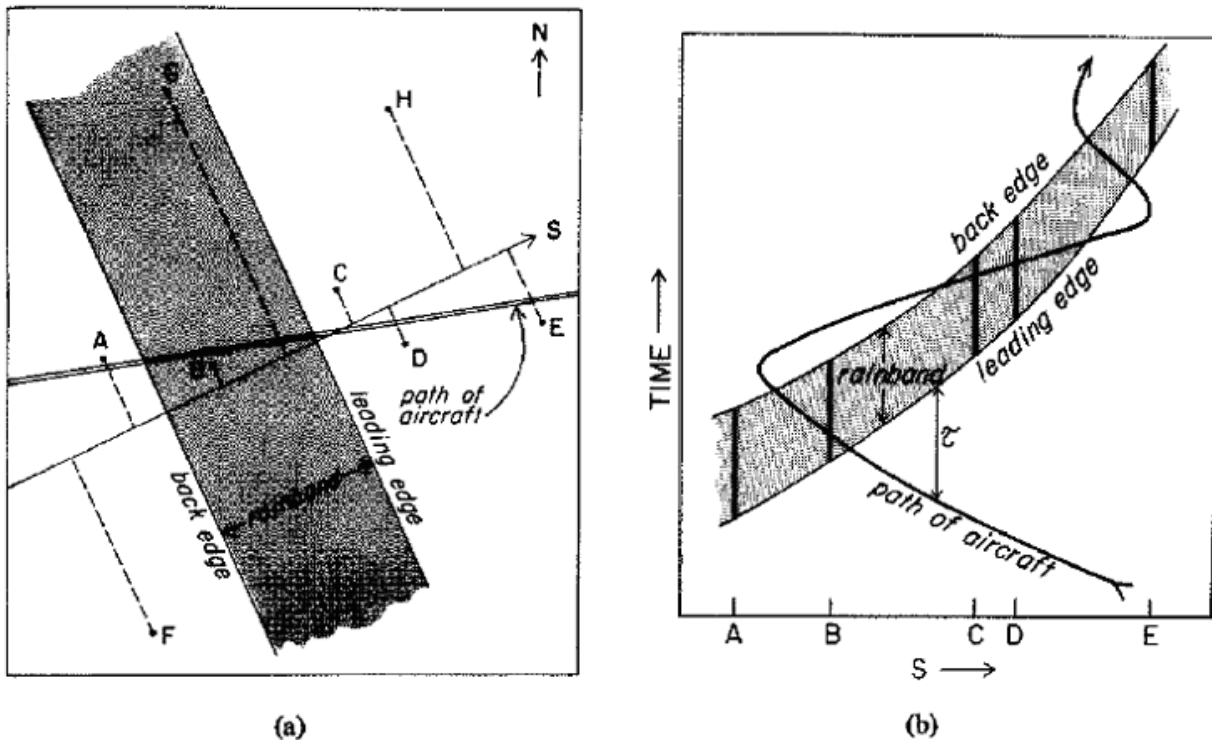
Figure 5.1 - Illustration of two steps in the method by which the research aircraft may be positioned relative to a convective band. The horizontal axis is perpendicular to band labeled S. In (a), sites A-H are stations having precipitation records. In (b), heavy bars represent the periods of stations A-E during which precipitation fell from the rainband. See Matejka et al 1980 for details. Copyright Quarterly Journal of the Royal Meteorological Society, used with permission.

2. The aircraft will ascend to the -5°C level and conduct a penetration according to the flight pattern shown in Figure 5.1a with the distance between A and E in Figure 5.1b, being the part or the region of the cloud band or structure that will enter the target region. During this time the aircraft will relay to the Operations Center the region of maximum observed liquid water contents. Assuming that this region will be aligned along the length of the cloud band and/or structure, the Operations Director will map a seeding path through this region of maximum liquid water content.

3. The Operations Director will subsequently provide the path coordinates to the seeding aircraft, which will fly along a line at the highest level within the cloud that SLW is consistently found. This will maximize on-station time, and reduce airframe icing. Seeding will commence as soon as the seeding aircraft enters the region of supercooled liquid water content.

4. If additional cloud bands and/or structures are anticipated to enter the target region the Operations Director will guide the seeding aircraft to these clouds and the same procedure as previous will commence.

5. Seeding will be conducted until 20 minutes before the cloud bands and/or structures are predicted to exit the target region as determined by the model predictions and the available radar data.

Cap Clouds. When cap clouds are present, visual meteorological conditions (VMC) may often exist upwind of the targets. In such cases, the aircraft should fly repeated passes on the upwind

edge of the cap cloud, but should make penetrations for microphysical documentation purposes. The flight pattern will be coordinated by the Operations Director, in general being as follows:

1. After take-off the aircraft should proceed to airspace upwind of the cap cloud, at approximately the cap cloud altitude. This may be on either the eastern or western sides of the targets, depending upon the cap cloud-producing wind direction. Because of the lack of synoptic features that enhance vertical motions, cap clouds are quite often of limited spatial extent, such that little time is available for precipitation growth and fallout.
2. With cap clouds it is important to initiate precipitation at the earliest possible moment; therefore seeding with aircraft along the leading edge of the supercooled cloud will afford maximum ice crystal (snowflake) growth times, and produce the maximum amount of snow. Because of the limited spatial extent of cap clouds, any additional snow produced by seeding will fall in the higher elevations.
3. Seeding will continue as long as the supercooled cap cloud persists. If the aircraft on-station time becomes a limiting factor, the aircraft should return to base, refuel and add seeding agent, and return to seeding as quickly as possible.

Convective Clouds. Convection (cumuliform clouds, clouds of vertical development) is most common in the autumn and spring, when low level temperatures are warmer, but temperatures aloft can be quite cold. This sharp vertical temperature gradient results in an unstable atmosphere, and this instability, often released by forced orographic lifting, generates cumulus cloud towers, often embedded within cap clouds or broader synoptic-scale storms. These towers are invariably supercooled, and well suited to seeding by aircraft.

1. To seed embedded convection, the most immediate effects can be realized through the direct injection of glaciogenic seeding agent at cloud top. This must be done by penetration of the cloud top during which ejectable pyrotechnics are released into supercooled updrafts.
2. The treatment altitude of the aircraft should be between -5 and -10°C when possible. Though this may initially sound rather warm for wintertime seeding, the reader must remember that convection will be most common in the autumn and spring.
3. The treatment altitude must be high enough above the height of the maximum terrain below that there will be no possibility of the pyrotechnic reaching the surface. This is essential to avoid all possibility of fire. Thus, there will exist a minimum altitude below which ejectable flares can never be used. In some cases, convective clouds will not be tall enough to be treated with glaciogenic agents, even if cold enough.
4. If supercooled convective turrets exist, but are not tall enough to ensure that ejectable flares would be completely burned during freefall and well before having any chance to reach the surface, such turrets can be seeded by aircraft penetration with burn-in-place flares.

Seeding runs are normally done at relatively low speeds (approximately 140 kts) which, in turn, assist the pilot in finding indications of updrafts and supercooled liquid water, by observing vertical and horizontal speeds of the aircrafts, as well as physically feeling the air motions. Airframe icing will also be an important indicator of supercooled liquid water (SLW) content. The seeding application's success depends purely on the pilot's accuracy in dispersing the seeding material in the locations dictated by the observed clouds and airflow (winds).

Icing conditions may be a concern during penetrations. Within safety margins, the pilot may have to maneuver the aircraft in a way that might be seen as unusual by observers not

accustomed to cloud seeding operations. However, these maneuvers are sometimes necessary to seed in the maximum convective updraft and SLW regions.

Ground-based ice nuclei generators should be burned continuously while supercooled clouds exist. However, the pilot may choose to suspend seeding in order to fly away from the storm and perhaps gain altitude to get a clearer picture of the position of any new development, and the Operations Director may modify the seeding pattern.

If the clouds deteriorate to the point where seeding is not considered effective (i.e. when the vertical motion ceases or humidity decreases to the point that no liquid water exists or the cloud dissipates) seeding should be terminated.

5.2.4   When Not to Seed

It is critically important that all cloud seeding programs include in their published design and operations plans, criteria that will trigger the immediate cessation of seeding activities. For example, many programs do not attempt to seed large storm systems that are forecast to produce heavy snows. The reasons for not seeding are two-fold: (1) such storms are normally vertically deep, cold, and naturally efficient and (2) such storms often naturally lead to the closure of public roads, and may even result in avalanche conditions. Not seeding large storms, especially when there is little to be gained (for nature is efficient in such cases), makes a great deal of sense. The mesoscale real-time forecast model used for operations may be used to determine which regions of the target areas are likely to experience significant snowfall.

Winter orographic seeding programs should also have additional seeding suspension criteria that result in the cessation of seeding when a certain percentage of normal snowpack is observed within the target area(s). For example, early in the season when total snowpack is not great (1 December, perhaps), seeding might cease if/when snowpack reaches 200 percent of normal. As the season progresses and the snowpack increases, this percentage should decrease, so that by 1 January the criterion might be 175 percent of normal, by 1 February, 150 percent of normal, and by 1 March, 130 percent of normal. *These numbers are provided only as examples.* The numbers appropriate for the two proposed Wyoming target areas should be established by consultation with the WWDC and other agency hydrologists, who are intimately familiar with the areas, and can provide meaningful data regarding the established relationships between snowpack evolution and streamflows. Output from the NOAA Hydrometeorologic Prediction Center, SNOTEL, and the SNODAS websites should be used to closely monitor snowpack evolution.

Because both of the proposed target areas are very expansive, it would make a great deal of sense to treat each target are separately in implementing suspension criteria. It would also make good sense to subdivide each of the targets into zones.

For example, if the suspension criteria triggered by accumulated snowpack were triggered in the north end of the Wind River Range, snowpack further south might very well be considerably, and seeding still desirable. Such "zones" should be defined in concert with the seeding suspension criteria themselves, and included in the project operations manual.

To ensure that the program suspension criteria consider all factors that might significantly contribute to winter hazards, it is recommended that an Operation Criteria Development Team be created. Such a team would include the WWDC, the NWS, the Wyoming State Engineer's

Office, the Forest Service, the Bureau of Land Management, the Wyoming Department of Transportation, and others.

5.3   Project Coordination

There are numerous components to this field project, including forecasting and operational decision making, cloud seeding operations, maintenance, and post-processing of data. Clear communication and collaboration between participants are essential for the success of this project. The overall coordination of the project will be done by the Operations Director. The Operations Director should be a meteorologist familiar with running field programs and will be responsible, in collaboration with staff, for the conduct of operations. The Operations Director should work from the Operations Center, and should manage and direct the day-to-day operations and personnel. This person's duties will involve management of generator and aircraft operations, including general aircraft guidance, and ensuring that the proper data collection is taking place. The WWDC and the State Engineer's Office will oversee the Operations Director, who should be responsible for scheduling all operations, taking into consideration all available meteorological data, including local soundings and weather forecasts, and classifying the day into one of the categories listed in Table 5.1. He/She will also coordinate with other agencies for logistical needs.

More specific duties of the Operations Director should include:
- Consultation of staff forecasters and conduct of the morning weather briefing.
- Determination of operational status based on forecast and generator and aircraft readiness.
- Informing all field personnel and interested parties on planned operations for the day.
- Development of daily plans for ground-based generator activation, after consideration of numerical model output.
- Development of daily flight plans, in consultation with the pilots.
- Direction of aircraft operations from the Operations Center.
- Ensuring that all requisite reporting is conducted in timely way.
- Dissemination of weather outlook and tentative plan for the following day.
- Notification of all crew members when they may stand down for the day.
- Determination of down days for the project staff.

Table 5.1 - The Daily Code and Crew Readiness

STATUS	% Chance of Seedable Clouds	Comment	Crew Readiness
RED	60% - 100%	There will likely be suitable clouds	Crews ready
ORANGE	30% - 59%	Medium chance of suitable clouds	Crews ready
YELLOW	10% - 30%	Small chance of suitable clouds	Crews one hour from being ready
GREEN	0% - 10%	No chance of suitable clouds	Crews stand down

6.   ENVIRONMENTAL AND LEGAL ASPECTS

This section provides an overview of the primary environmental and legal aspects of the proposed programs. Additional information regarding the permitting and reporting requirements is provided in Section 7.

Forefront in the "environmental" arena is the question basic to the feasibility of the programs themselves: Can enough additional snow (water) be produced, without adverse downstream impacts, to make the cost of the program worthwhile? In beginning to answer this question, we first examine what others have been able to achieve and the view of the scientific community as a whole.

The benefits of the potential projects are addressed in Section 10.   Preliminary cost estimates are provided in Section 11, and a preliminary benefit-to-cost analysis is presented in Section 12.

6.1   Some Findings from Other Projects

The American Meteorological Society, in its *Policy Statement on Planned and Inadvertent Weather Modification* (1998), notes that present statistical evidence suggests seasonal snowfall increases of about 10% have been achieved. However, estimates from a number of long-term operational projects in the United States and elsewhere suggest seasonal increases up to 15%. The project closest to the proposed Wyoming targets, the Bridger Range Experiment, showed increases of 15% (Super and Heimbach 1983).   The Hydro Tasmania winter orographic program has realized increases on the order of 20% (Ryan and King 1997).

The findings from numerous scientific cloud seeding programs in the western U.S. were examined and summarized by Super (1999a) along with their various methodologies. Super indicates that there is considerable potential to increase snowpack through cloud seeding but only thorough well-designed, well-documented programs that include verification of the proper targeting of the seeding agents.

This having been stated, the following essential points are noted, each very relevant to winter orographic clouds over western North America, including Wyoming:

1. Many winter orographic clouds, especially those associated with deeper, colder storms, are naturally efficient with abundant ice particle concentrations which convert virtually all available SLW cloud to ice. However, it has also been well documented over mountain ranges in Arizona, California, Colorado, Montana, Nevada and Utah that when many orographic clouds have limited natural ice particle concentrations, little of the available SLW is converted to snowfall (Super 1999a). The means exist to create large concentrations of additional ice crystals in such inefficient clouds. Any given storm passage of several hours duration may alternate a number of times between naturally efficient and inefficient phases. Some shallow orographic storms may have abundant SLW and almost no precipitation over many consecutive hours. Without local information regarding the presence of excess SLW and cloud temperatures, it cannot be unequivocally stated how often such conditions exist. However, given the observed frequency of Wyoming storms during 2003-2004, it is likely that seeding may be feasible six to ten times per month. Seeding in each event may vary from an hour or two to many hours, depending upon the persistence of suitable clouds.

2. Observations over several mountain ranges have indicated that the inefficient storm phases have SLW flux that, if converted to snowfall, would be equivalent to a large fraction of the natural snowfall. Even if only a portion of these potentially seedable phases could be successfully treated, seasonal snow water content increases in the range of 5 to 15% could likely be realized. Such increases would significantly enhance the warm season runoff.

3. The bulk of the SLW-bearing cloud volume is usually found upwind of and over the windward slope and crest of mountain barriers where orographically-induced upward motion and thus liquid condensate production are greatest. Downward motion (subsidence) over the lee slope rapidly causes the evaporation of tiny cloud droplets and sublimation of small ice crystals. Often, much SLW is located within 500 m (1,700 ft) above the crest line with very little found more than 1.0 km (3,300 ft) above the crests. Cloud bases over the Park Range of northern Colorado were usually observed to be between 200 to 300 m (650 to 1000 ft) below the crest line during snowfall, although cloud bases ranged from 500 m to 50 m (1,650 to 165 ft) above the crest (Rauber and Grant 1986). However, the WRF modeling reported herein shows the repeated presence of SLW at heights greater than those targetable solely by ground based seeding owing to the development and persistence of gravity waves. This has ramifications for cloud seeding by aircraft.

4. The temperature range of the SLW layer observed over the Park Range by Rauber and Grant (1986), and over the Grand Mesa of West-Central Colorado by Super et al. (1986) varied from about -5 to -15°C, and -4 to -10°C, respectively. These temperature ranges are on the "warm" side of what only a few years ago was considered by most to be the range of silver iodide-based seeding agents. However, recent tests of pyrotechnic formulations (those manufactured by Ice Crystal Engineering of Davenport, North Dakota) at the Colorado State University (CSU) Cloud Simulation and Aerosol Laboratory (SimLab) have confirmed ice production on the order of 10^{11} nuclei per gram, effective at –4°C, independent of cloud water content (DeMott 1999). Thus, the window of opportunity for glaciogenic seeding has been increased. In addition, the proposed target area for this program is significantly further north, and therefore likely to be somewhat cooler as well.

5. Effective seeding of winter orographic clouds ultimately becomes a race against time, as seeded crystals are transported quasi-horizontally through the SLW cloud, over the mountain crest, and then, if not precipitated, downwind. Seeding-generated embryonic ice crystals have a limited time and distance in which to grow large enough to fall to the mountain surface. Otherwise, they are carried into the lee subsidence zone immediately downwind from the mountain barrier where warming quickly evaporates the minute cloud droplets and more slowly sublimates the much larger, yet unprecipitated ice particles.

6. Cloud seeding can be done effectively with aircraft releases of the seeding agent or by high-altitude, ground-based releases. Aircraft operations allow more flexible targeting. High altitude ground-based seeding is an approach that has been shown to routinely target the orographic SLW zones typically concentrated very near the mountain surface. It is best to site high-altitude silver iodide generators where they will often be within cloud or not far below cloud base where ice saturation exists. If so sited, large numbers of embryonic ice crystals will be created within a very short distance downwind from the seeding generators. In effect, such seeding releases ice crystals into the SLW cloud which then grow even as they are transported upslope. Moreover, silver iodide is effective at temperatures as warm as -4°C in this mode with commercially-available seeding agents.

Of course, different storms are affected differently by seeding. Naturally efficient storms, generally those that produce the most snowfall, will likely be affected little. Conversely, long periods of slightly supercooled, persistent orographic cloud can often be effectively seeded resulting in many hours of continuous light snow when none would have fallen naturally. Collectively, over the course of a winter season, these increases typically amount to about 10% of the natural snowfall (Super).

6.2   Ecological Effects

Standler and Vonnegut (1972) provided estimates based on medical and meteorological literature demonstrating that the extremely low silver concentrations found in seeded precipitation posed no danger to human health. Sokol and Klein (1975) investigated soil surrounding an AgI seeding generator in the Park Range of Colorado and indicated that the much lower silver concentrations in seeded target areas should have no serious effects on the soil microbial environment. However, they recommended monitoring of target areas subjected to AgI seeding over very long periods.

In a cloud seeding feasibility study for BC Hydro (British Columbia, Canada, Boe et al. 2001), calculations based on the amount of seeding agent likely to be used during a season indicated the maximum possible concentration of silver in the resulting water would not exceed 10^{-10} (0.0001 milligrams per Liter), some three orders of magnitude (1000 times) below the accepted U.S. Environmental Protection Agency standards for drinking water. This assumes no dilution by unseeded water, even though the seeding-produced water would be a small fraction of the total in the reservoir. These calculations were intended as approximations only, and should be considered as such.

Frank (1973) concluded that a 10% increase in snowpack due to cloud seeding would have little, if any, immediate effect on mountain grassland productivity in western Colorado. Similarly, Weaver and Super (1973) and Weaver (1974) investigated mountain meadows within the target area of the Bridger Range Experiment in southwestern Montana. Weaver and Super (1973) concluded that harmful effects were not expected from silver deposited over 100 years or less and that 20% snowfall increases were unlikely to significantly affect vegetation of fescue meadows typical of the target area. Weaver (1974) used aerial photography to identify durations of snow cover and later measured meadow diversity, cover and productivity. He concluded that 10 to 15% snowfall increases in seeded target areas would have only small effects. Weaver and Collins (1977) used snow fences to artificially induce drifts on a large mountain meadow in the Bridger Range. They stated that, "It appears that the impact of seeding winter orographic clouds for 10 to 30% increases in snowfall on the vegetation of *Festuca idahoensis* meadows would be slight."

A large body of environmental information may be found in the final reports of the following major investigations and in their numerous references. One of the first major studies, which has frequently been cited, is by Cooper and Jolly (1969). They performed a valuable problem analysis of the ecological effects of cloud seeding.

A comprehensive study conducted by the University of Wyoming and the U.S. Forest Service was concerned with winter cloud seeding in the Medicine Bow Mountains of southeastern Wyoming (Knight et al. 1975). The study reviewed the geology and soils, natural silver concentrations, climate, hydrology, snow duration and microseason climate in alpine tundra and subalpine meadows, the impacts of additional snow on elk, mule deer, and vegetation, and a number of other topics including the potential toxicity of silver iodide in the ecosystem. The

study concluded that, "The lakes will not suffer any perturbation that would not occur in the absence of cloud seeding", and that "A fifteen percent increase in snowpack would probably not affect trout production greatly." The report notes that, "The production of trout and benthic invertebrates apparently are influenced as much by variations in the pattern of the runoff and late summer air temperatures as by the amount of snow and runoff." In addition, Knight et al. (1975) state that, "Our data suggest that the amount of AgI added to the soil by cloud seeding will not have adverse effects on lodgepole pine and tufted hairgrass seedlings until such concentrations become between 100 and 1,000 times those naturally found in the soils of the Medicine Bows. *It would take 450 years for cloud seeding to double the natural silver concentration in the soils of the Medicine Bow Mountains*, except near ground-based generators." The reader is referred to Knight et al. (1975) for additional details of this fascinating and multifaceted research program.

Another major investigation into environmental effects of winter cloud seeding was conducted in the San Juan Mountains of southwestern Colorado as reported by Steinhoff and Ives (1976).

The Uinta Ecology Project, reported by Harper (1981), is yet another major study in the general area of the Headwaters Region. It dealt with potential ecological impacts of increased snowfall on the Uinta Mountains of northeast Utah which extend into southwest Wyoming.

The multi-volume Sierra Ecology Project reports address the potential ecological impacts of cloud modification on the Sierra Nevada and contain considerable useful information. In particular, Volume Four, by Smith and Berg (1979), provides an extensive bibliography on the environmental effects of weather modification.

Howell (1977) considered several research projects into weather modification impacts on the environment and provided numerous references. He noted that, "Studies of physical and biological processes relating precipitation and ecosystem changes show relatively few discernible effects, all of them minor in nature and magnitude. Direct effects of nucleating agents no longer appear consequential." Howell (1977) acknowledged that possible long-term effects on ecosystems deserved further attention.

All of the evidence at hand suggests that the aggregate environmental impact of the program will be manageable. It is herein recommended, however, that reasonable steps be taken to monitor the presence of residual seeding agent in the environment and to fully assess the effects of seeding upon the precipitation, both within and downwind of the target area. The latter is discussed in greater detail below.

6.3   Extended Area Effects

Many people think of the atmosphere as more or less a water pipeline rather than as a part of the hydrologic cycle. If that were the case, it might seem logical that using cloud seeding to increase snowfall on a mountain barrier would leave significantly less moisture for downstream areas. The notion that cloud seeding might "rob Peter to pay Paul" has been voiced many times during the modern era of cloud seeding. Some downstream water users are therefore concerned that upwind seeding projects may be "stealing" their water.

In reality, the atmosphere is not confined to the walls of a pipe, and consequently behaves little like a pipeline. The production of the liquid water condensate that becomes clouds is governed by humidity and vertical motions in the atmosphere, constrained by the temperature profile,

winds, and topography. Sustained upward motions result in cooling, which in turn produces cloud droplets when 100% relative humidity is achieved. Downward motions rapidly evaporate the tiny cloud droplets as the relative humidity quickly falls below 100%. Airflow over mountains is but one process resulting in cloud production and decay.

Large scale atmospheric motions related to cold fronts and low pressure centers are primarily responsible for liquid cloud formation and dissipation within widespread winter storms. Usually, the orographic uplift and lee descent caused by a mountain barrier are superimposed on a much larger scale but less intense vertical motion field that produces widespread cloudiness; that is, a storm. The result is that unless upward motion is imposed upon an already moist atmosphere, clouds will not form, and snow cannot fall.

To gain an increased appreciation for the moisture budget in a typical Wyoming winter storm, representative temperature and moisture profiles (from Riverton NWS soundings) were examined in the context of orographic flow. A typical wintertime moist air flow approaching the Wind River Mountains in storm conditions, at a height of 3.0 km (10,000 ft) above mean sea level (MSL), at a pressure of about 700 hPa, might have a temperature of about -10°C, and a relative humidity of about 90%, meaning a dew point temperature of about -11°C. As the moist flow encounters the mountains, it is forced upward. As it rises, it cools, and clouds and precipitation form over the mountains. Nature typically will condense just over 20% of the total water vapor in the air, rising up and over the mountains. The other 80% of the moisture remains uncondensed, because the air containing it never gets nearly cold enough to condense it all. Winter storms are typically about 30% efficient, so 30% of the 20%, or about 6% of the total moisture, ends up falling out naturally as precipitation. If cloud seeding is successful in increasing the natural precipitation by 15%, that amounts to 15% of the 6%, or about 0.9% more of the total atmospheric water that might be precipitated when seeding is conducted (Figure 6.1). These thermodynamic calculations do not consider that within the hydrologic cycle, this additional water, now on the ground instead of in the air, is not "gone", but is now available to sublimate, and to be transpired by plants back into the air.
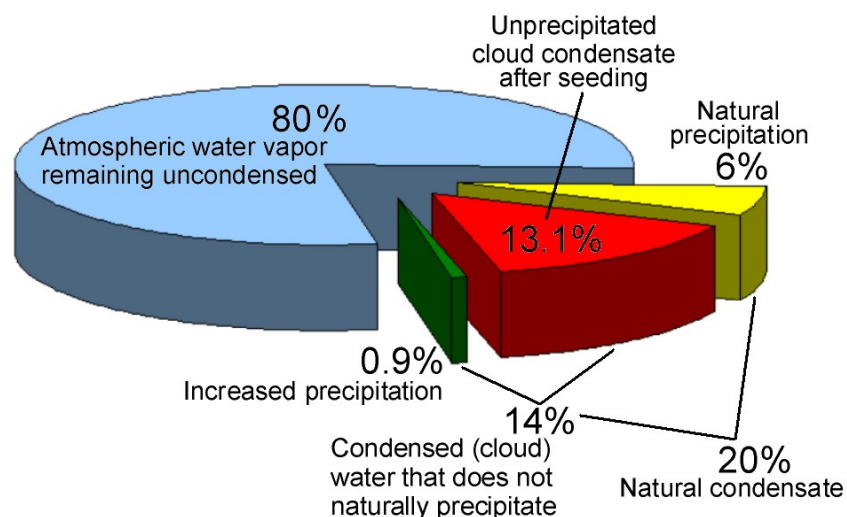
Figure 6.1 - Pie-chart illustration of distribution of atmospheric water vapor when cloud seeding results in a 15% increase in precipitation.

Moisture remaining on the ground may contribute to eventual runoff (and re-evaporation from surface water bodies), or may be tapped by plant life if it infiltrates the soil. Moreover, not all of

the atmosphere is ever seeded, nor are seeding operations ever continuous. Thus, the net effect of cloud seeding upon the atmospheric water budget is no doubt only a fraction of the 0.9% calculated here. Conversations with Mr. Joe Sullivan, Meteorologist-In-Charge of the Riverton Weather Service Office, confirmed that the instrumentation presently used on the NWS weather balloons, would have a difficult time detecting a change on the order of 1%. Net increases in precipitation on the order of 15% are possible only because that atmosphere as a whole naturally converts *very little* of its total moisture to precipitation.

This exercise was repeated for a variety of wintertime temperature regimes and atmospheric moisture contents, and yielded very similar results. This finding should be very reassuring to those downwind, as the net difference in atmospheric moisture downwind, presuming no positive feedback from seeding, is less than the accuracy of the instrumentation used to measure it.

The removal by cloud seeding of a tiny percentage of the vertically-integrated water (vapor plus liquid plus ice) in the atmosphere is very minor compared to the overriding influence of large scale motions.

The water content of the atmosphere over downwind mountain ranges is generally similar to that over the seeded range less the percentage extracted by natural and seeded precipitation. As discussed previously, and illustrated in Figure 6.1, there is a slight difference and that is due primarily to the natural precipitation. Downwind precipitation on the plains is generated by synoptic and convective motions and is fueled by a new source of water, generally the Gulf of Mexico.

The potential for possible "downwind effects" or "extended area effects" of cloud seeding has been given serious consideration for some time. Downwind persistence of silver iodide and dynamic effects of seeding are two reasonable hypotheses for considering such effects. Though the proposed seeding program would use silver iodide-based ice nuclei, the wintertime atmosphere is generally quite stable so the resultant latent heat released by seeding-induced freezing would not trigger significant instability and it can be assumed that associated dynamic effects would be negligible.

Ice crystals created by seeding would be subjected to the same descent and subsequent sublimation as natural ice crystals as they pass over the crest line downwind of the seeding generators and aircraft and would likely not survive. However, there is a possibility that the ice nuclei themselves might survive in the atmosphere, if not scavenged by other precipitation, and could thus be in a position to initiate new ice growth during renewed ascent upwind and over the next mountain range. In the Sierra Madre/Medicine Bow target area, however, the upwind (westward) slope of the Medicine Bows is also within the intended target, so even should precipitation result in the Medicine Bows as a result of seeding the Sierra Madre Range, any effect would still be within the Platte Basin.

Some relevant research on this subject was done by Hindman (1986), who presented calculations of the wintertime water balance over the Park Range of Colorado. He showed an average of 9% of the inflow moisture was precipitated on the barrier. Assuming 10 to 15% seasonal increases from cloud seeding, Hindman (1986) concluded that, "It was found that, on average, a small amount of atmospheric moisture precipitates on the mountain barrier (6 to 14%). Cloud seeding activities are estimated to increase these values 1.3%. This value is very close to the 0.9% value derived previously in this section for the Wind River Mountains.

Hindman (1986) concludes "Cloud seeding activities on the upwind Park Range barrier should not rob moisture from the downwind Front Range barrier."

A more recent controversy arose as the result of worries about the possibility of decreased snowfall downwind caused by operational seeding of clouds over the Uinta Mountains of northeastern Utah and southwestern Wyoming. As a result, two university groups were funded by the State of Utah to pursue investigations relevant to possible extended-area effects. One group pursued statistical analyses of precipitation gage and snow course observations using a target-control approach with the non-randomized dataset. The other group evaluated the climatology of winter storms in the Uinta Basin.

Grant and Mielke (1990) addressed the probability that cloud seeding upwind from the Uinta Mountains, and specifically in the Wasatch Range of Utah, was affecting precipitation in the Uinta Mountains and Basin. The possibility of either negative or positive precipitation changes were considered, in a statistical analysis, as no direct physical evidence was available. The authors acknowledged this and noted that highly definitive results should not be expected. Both precipitation gauge and snow course observations were included in their study. In spite of these difficulties, Grant and Mielke (1990) were rather positive in their findings. They concluded that "The results for both the seeded target and downwind areas are consistent with the results of analyses of other research and operational cloud seeding programs of wintertime cloud seeding in mountainous areas. These analyses in other areas have generally shown precipitation increases in such seeded areas to be in the range of 10-15%, considerably higher under some weather situations but lower or negligible with others. These results are also compatible with consistent indications of an increase in precipitation in the 25 to 100 mile area downwind from wintertime, orographic cloud seeding programs in other areas." However, the findings of Grant and Mielke (1990) were not statistically significant. The results should thus be considered only suggestive, not as unequivocal proof of a positive downwind effect. The most likely reason for this is that the magnitude of the perceived effect is small, and thus more difficult to demonstrate with statistical significance.

An analysis of cloud seeding operations conducted in northern Utah was made to provide an estimation of cloud seeding effects on precipitation for targeted areas and for downwind areas in northeastern Utah and southwestern Wyoming (Grant et al. 1992). Analyses were made for nine designated areas. The use of a nonparametric technique on residuals where the nontreated values were obtained by regression on an ample historical base allowed greater flexibility in the analysis. The one-sided P-values of these analyses were all based on the two-sample Wilcoxon-Mann-Whitney rank test. Two mountainous areas were downwind of intentional Utah cloud seeding programs on at least some occasions. Of primary interest was the Uinta Range of northeastern Utah. The other was the more distant Park Range of northern Colorado, which extends into southern Wyoming. Both the snow course and precipitation analyses for these areas show that while the seeded period values were most frequently slightly greater than expected, the precipitation in these downwind areas was very close to expected amounts and to that expected by chance. There was no consistent pattern in precipitation differences during the seeded periods in the downwind non-mountainous areas studied (North of Uintas; South of Uintas; Northeast of the Wasatch; and the Pinedale, Wyoming area). In summary: the precipitation analyses of areas downwind of intentionally seeded areas showed snowfall and precipitation amounts very close to that which would be expected (Grant et al. 1992). There was a very slight, but certainly not anywhere near statistically significant, tendency for precipitation to have been *slightly greater* (not less) during seeded periods than would have been expected. Thus, the analyses of all downwind areas indicated that

precipitation in those areas during upwind seeding programs was very close that expected, with a high probability that there was no effect from seeding.

Jensen et al. (1990) developed winter storm climatology for the Uinta Basin and the Wasatch Front to evaluate Utah terrain and its effect on orographic precipitation patterns. They concluded that much of the Uinta Basin precipitation results from storms from southerly directions. The Uintas are oriented east-west, whereas most western mountain ranges are oriented north-south. Jensen et al. (1990) made the important point that wet and dry periods in Utah and the Uinta Basin are largely influenced with large scale atmospheric conditions. They noted that most of the period 1979 through 1988 was normal to very wet in the Uinta Basin, but that the Uinta Basin began to suffer moderate drought by late 1988 and began to experience severe drought by the spring of 1989. That drought continued through the fall of 1990 when their report was published. Though not explicitly stated, this implies that the then-current local concerns about possible precipitation decreases downwind from seeding in the Uintas were actually the natural result of unfavorable large scale atmospheric conditions. That is, large scale flow and moisture patterns were causing dry conditions in the Uinta Basin which were perceived by some to be caused by cloud seeding.

7. PERMITTING AND REPORTING

7.1 Permitting

The permitting of weather modification programs in the State of Wyoming has long been the administrative duty of the Wyoming State Engineer's Office.

During the August 2004 scoping meetings, a representative of that office explained the requirements for permitting that existed at that time. However, she also noted that more stringent draft regulations were presently being proposed. As this report is being written, the new requirements are still in draft form and comment is still being received by the Wyoming State Engineer's Office.

Typically, the permitting process ensures that the person(s) responsible for the conduct of the actual seeding operations are knowledgeable, experienced, and responsible as demonstrated by their professional credentials.

In addition to the permitting of weather modification in the State of Wyoming, additional permits (Special Use Permits) will be required if any equipment is to be sited on Forest Service lands. This fee is US$75 per site payable once the permit itself has been approved. As mentioned previously, the siting of equipment, scientific or otherwise, at sites heretofore unused for such purposes on federal lands will likely invoke the National Environmental Policy Act (NEPA) through which an environmental assessment (EA) may be conducted. If an EA results in a finding of no significant impact (FONSI), then the permit may be granted and the appropriate fees paid. If "significant findings" result from the EA, then a complete environmental impact statement (EIS) would be required, thus delaying the onset of program operations.

Given the large number of previous studies that have found no significant impacts (e.g. Knight et al. 1975 for the Medicine Bows themselves), it is thought unlikely that a complete EIS will be necessary. However US$50,000 should be budgeted for each target area for the initial season to ensure that adequate funds will be available for any necessary environmental work in order that any necessary Forest Service Special Use Permits can be obtained in a timely fashion.

7.2 Reporting

Reporting is required on several levels. Informal reporting to local sponsors should be done in quasi-real time as much as possible. This will provide current knowledge of project seeding activities, suspensions, etc., and can be easily accomplished through a project web site. Such a site could be set up and maintained by the WWDC or by the project contractor.

Regular (monthly) reports should be made to the Wyoming State Engineer's Office whether the final rules for weather modification permitting require such reports or not. As a courtesy, the reports should be copied to the Forest Service, BLM, and the Tribes as well. It is better to disseminate too much information than not enough.

At the federal level, reporting prior to project start is required by the National Oceanic and Atmospheric Administration (NOAA) offices in Silver Spring, Maryland. These "initial" project reports must be filed prior to the beginning of each operational season and must include description of the area(s) to be targeted, the starting and proposed ending dates and a description of the seeding agents to be used. At the conclusion of the project, a report

describing the dates of all seeding activities and the amounts and types of each seeding agent dispersed on each day must be provided, as well as monthly totals. If the project continues for more than six months, an interim report may be required every three months while the program is ongoing, as well as the final report. There are no fees required by NOAA.

The proposed start and end dates for this program are 15 November through 31 March, inclusive, so the total project duration is 4.5 months and no interim report to NOAA should be needed.

8. ACCESS AND EASEMENTS

To determine the ownership of the lands in and near the two possible target areas, maps of the Medicine Bow, Shoshone and Bridger-Teton National forests were purchased. These maps show land ownership and classification by the following categories:

A.   *Private land.* This is land owned by individuals or corporations, but not by governmental entities.

B.   *Bureau of Land Management lands.* These are lands administered by the BLM.

C.   *State Public Use lands.* These are state-owned lands open to public use.

D.   *Indian Reservation lands.* For the purpose of this feasibility study, these lands are those of the Wind River Indian Reservation, home to the Northern Arapaho and Eastern Shoshone Tribes. The Reservation is jointly managed by combined government boards and councils comprised of members from both tribes.

E.   *Forest Service lands.* These are lands administered by the Forest Service, but not classified as wilderness.

F.   *Wilderness.* These lands are designated wilderness by statute and use is considerably restricted. Motorized vehicles of any type are prohibited. Rules for travel and camping within wilderness can be found on the web sites of each of the National Forests; for example, http://www.fs.fed.us/r4/btnf/offices/pinedale-we.shtml.

8.1 Access to and Use of Private Land

If privately-owned land is identified that is suitable for the siting of project meteorological and/or seeding equipment, arrangements and permission for the use of said lands must be obtained directly from the landowner. Depending upon the landowner, permission for use may be granted free-of-charge, granted for a fee negotiated by the parties involved or denied. Access to the lands may be through existing easements used by the owners, by adjacent public road or through other private lands. In the last case, easements must be negotiated with the other landowners over whom whose land one must pass to reach the selected sites.

It is very difficult to fix a cost to use of these lands for the reasons stated in the previous paragraph. If private land is identified as being an optimum location for equipment, it is recommended that access costs initially be budgeted as US$250 per site, per season. In many cases the landowner may be very willing to assist the program without charge, but this will not always be the case.

Preliminary screening of the land ownership in and near the two prospective target areas suggest that few sites will be on privately-owned lands, so it is recommended that the sum of US$1,000.00 be budgeted initially for each target area for this purpose.

8.2   Bureau of Land Management Lands

In many cases, BLM lands are directly adjacent to and upwind of the prospective targets areas; for example, thousands of acres of BLM land exist adjacent to and on the southwest side of the Bridger Wilderness of the Bridger-Teton National Park. Permission to site equipment on BLM land must also be obtained from the responsible local BLM office, but no fixed fees for such use are established. If access is available only through other private lands, permission (easements) must be obtained from those landowners, as in Section 8.1 preceding.

In the course of the August 2004 scoping meetings, a number of BLM staff represented the various regions and all were receptive to the idea. However, it must be noted that those staff persons attending the scoping meetings did and do not necessarily reflect the views of the agency itself.

Nevertheless, initial contacts with the BLM suggest that close coordination will be required and that siting of equipment on BLM land should not be problematic.

8.3   State Public Use Lands

Some state-owned lands designated for public use are also found upwind of the prospective target areas. If sites on such lands are tentatively identified, the WWDC, as the lead state agency, will coordinate initial contacts with the appropriate state agency, e.g., the Wyoming Office of State Lands and Investments.

8.4   Wind River Indian Reservation

The Northern Arapaho and Eastern Shoshone Tribes are sensitive to non-tribal access to reservation lands but have been receptive to the concept of cloud seeding to increase snowpack and runoff. A formal presentation to the Joint Tribal Water Board was made in Fort Washakie by WMI and WWDC staff on 1 September 2004.

No difficulty is anticipated in siting meteorological or seeding equipment on the reservation, provided that site installation and maintenance is coordinated with the tribes.

There are no Indian Reservation lands within or near the Sierra Madre or Medicine Bow Ranges.

8.5   Forest Service Lands

The USDA Forest Service has three national forests within the areas of interest. The Sierra Madre and Medicine Bow Ranges are contained within the Medicine Bow National Forest (Wyoming) and the Routt National Forest (Colorado). Since operations are initially planned only for Wyoming, only the Medicine Bow National Forest is involved. The Routt National Forest is supervised by the same Forest Supervisor; however, should the program ever expand south into Colorado, the same office would be involved.

The Wind River Mountains contain portions of two national forests. On the west side of the continental divide (Green River) lies a portion of the Bridger-Teton National Forest and on the eastern side (Wind River) lies the Shoshone National Forest.

Contact has been made with all three Forest Supervisors' Offices, and the U.S. Forest Service Liaison to the State. A letter from the Rocky Mountain Regional office of the Forest Service to the WWDC, dated 14 December 2004 stated: "We support your objective to provide a rigorous scientific study. If the pilot study is approved, the Forest Service and the Rocky Mountain Research Station of the Forest Service would like to discuss our role as potential partners in this study and/or in the independent validation and monitoring of the research. The Forest Service supports properly designed and scientifically and technically sound snow augmentation or other weather modification activities carried out by operators, provided those activities and anticipated results are consistent with all applicable laws and regulations governing the administration and management of National Forest System lands."

Siting of equipment within a National Forest requires the application for a special use permit. The application costs nothing, but the permit, if granted, costs US$75 per site. Application for a special use permit may trigger the National Environmental Policy Act (NEPA), which requires that an environmental evaluation be conducted. This could cost US$50,000 or more per target area to conduct such NEPA work. Though this would be a one-time cost and would cover all sites requested within that particular target area, those monies (US$100,000) should be budgeted for such purposes. It was also noted that if the request for siting comes from the state, a categorical exclusion may be granted, but there is no guarantee of this. It has been noted that if the project co-located instrumentation at existing sites (such as SNOTEL sites, microwave towers, etc.), siting could be much simpler, and the NEPA actions significantly eased.

To be conservative, it is recommended that US$50,000 be budgeted per project area for environmental work related to siting of equipment of non-wilderness Forest Service lands, and that an additional US$2,000 be budgeted for the Medicine Bow/Sierra Madre project area for special use permits, and an additional US$2,000 be budgeted for the Wind River project area.

8.6   Wilderness

Because the area covered by designated wilderness in each of the two potential target areas is so different, each will be discussed separately.

The Medicine Bow - Sierra Madre Target Area
There are four wilderness areas within these ranges: the Platte River Wilderness, the Savage Run Wilderness, the Huston Park Wilderness, and the Encampment Wilderness (Figure 8.1). Collectively, these are a small fraction of the total target. Prohibition of motorized vehicles within wilderness areas would make siting of any equipment very time consuming and labor intensive. Given the relatively small sizes of these wilderness areas, it is recommended that sites outside these areas be sought. Such an approach ought to allow the selection of suitable sites without siting anything in any wilderness area.

The Wind River Range Target Area
There are three wilderness areas within the Wind River Range: the Popo Agie and Fitzpatrick Wildernesses east of the continental divide and within the Shoshone National Forest, and the Bridger Wilderness west of the continental divide in the Bridger-Teton National Forest.

Figure 8.1 - The seven wilderness areas within the proposed target areas are shown in this map of the State of Wyoming. The Medicine Bow/Sierra Madre target in the southeastern portion of the state includes the Encampment River, Huston Park, Savage Run, and Platte River Wildernesses. The Wind River target area includes the Fitzpatrick and Popo Agie Wilderness Areas on the east side of the continental divide and the Bridger Wilderness Area on the western side.

According to Forest Service Regulations, the following rules apply to weather modification in wilderness areas:

> *2323.45 – Weather Modification Over Wilderness. Do not permit long-term weather modification programs that produce, during any part of successive years, a repeated or prolonged change in the weather directly affecting wilderness areas. See FSM 2323.04 for approvals. Approve wilderness as a target area for weather modification only when:*

> *1.   The proponent can provide scientifically supportable evidence that the activities will not produce permanent, substantial changes in natural conditions.*

> *2.   The proposal includes no feature that will visibly alter or otherwise impact the wilderness environment.*

> *3.   The proposal includes no feature that is likely to reduce the value of wilderness for recreation, scenic, scientific, educational, conservation, or historical use.*

> *Short-term weather modification activities that produce only occasional, incidental, temporary, or transitory changes in the weather with carryover ground effects that last only a few days beyond the actual cloud seeding period may be permitted.*

And, for approvals:

> *2323.04b – Chief. The Chief is responsible for approving:*
>
> *6.   Weather modification proposals or activities or installations resulting in weather modification that affects wilderness.*

Though the wilderness areas in the Wind River Range are large and contain much of the higher terrain, the State will exhaustively pursue all feasible equipment siting alternatives, so that wilderness siting can be avoided. Airborne seeding could mitigate such need in some locations, but in some weather conditions, aircraft operations may not be safe, and thus will not be possible.

In either case, it is recommended that project proponents work with the Forest Service, the BLM, the NWS, and others in refining project suspension criteria (see Sections 5 and 6), to ensure that (a) the requirements set forth in FSM 2323.45 are met, and (b) Forest Supervisors and District Rangers are involved, informed, and aware of all activities.

Because the requirements for conducting operations in wilderness areas are stringent, it may not be possible to do so by the fall of 2005 even if funding is obtained and all steps to gain approvals are taken in a timely fashion. Should this be the case, it is recommended that 2005 seeding activities in the Wind Rivers proceed only in areas where siting of equipment within wilderness areas will not be required and special-use permits can be acquired, or where seeding can be accomplished by airborne means.

9.   EVALUATION METHODOLOGY

9.1   General Background

9.1.1   Methods of Evaluation

The evidence required in establishing that a cloud seeding methodology is "scientifically proven" can be divided into two aspects. The first is "statistical evidence". Statistical evidence constitutes a statistical experiment based on the seeding conceptual model that is designed, conducted and evaluated in accordance with accepted statistical principles and procedures, and results in the rejection of the null hypothesis at an appropriate level of statistical significance. The statistical evaluation enables the detection, in an as unbiased manner as possible, of a change (seeding signal) in a response variable, as specified by the seeding conceptual model, which is usually relatively small compared to its natural variability. This is most efficiently accomplished by means of a suitably designed, randomized statistical experiment.

The second is "physical evidence". Physical evidence constitutes the measurement of key links in the chain of events associated with the seeding conceptual model and establishes the physical plausibility that seeding effects suggested by the results of a statistical experiment could have been caused by the seeding intervention. The seeding conceptual model determines recognition of seeding opportunities, implementation of a seeding strategy, and the evaluation of the effects of seeding. The physical evidence enables the establishment of a cause-and-effect relationship between the seeding intervention and the changes in the response variables as documented in the statistical evaluation. This is usually accomplished: 1) By means case studies of the behavior of seeded and unseeded clouds that are conducted on a sample of clouds involved in the statistical experiment or separate from it; and 2) As an integral part of the statistical experiment through the identification of a series of response variables associated with the seeding conceptual model. Response variables are parameters that represent key links in the chain of physical events as described by the seeding conceptual model. Such parameters must be capable of being measured to the degree necessary to discern the anticipated changes due to the seeding intervention.

The key benefits of a physical evaluation are provided in: 1) The information needed to determine whether or not the seeding conceptual model is working as postulated and, if not, why and where it is different; 2) The information needed to determine if and how the seeding methodology can be improved (optimized); and finally 3) The information needed to determine the conditions under which the seeding methodology can be used in other geographical locations (transferability criteria) – within the same region, the same country, and elsewhere in the world.

9.1.2   Physical Evidence

There are several different physical pathways (often called mechanisms) through which precipitation may form in natural clouds. Local conditions of updraft speed, temperature, pressure, initial aerosol characteristics, and cloud and precipitation particle concentrations and size distributions govern the rates of progress along these pathways. Several mechanisms may be active simultaneously, each affecting the others. Often one of the mechanisms proceeds faster than the others and becomes dominant. For the purposes of this report, and at the risk of oversimplification, it is useful to group these mechanisms into those that involve the formation of ice particles and those that do not.

When ice-forming agents are released directly into the top of a supercooled stratus cloud, there is little questioning whether it reaches a susceptible region of cloud. When the seeding agent is released directly into the updraft under a convective cloud it will become part of the updraft and presumably will be carried to a level where it can be effective.

In the case of area-wide sub-cloud seeding and orographic seeding, the agent usually is released upwind of the target. Whether it reaches the intended target, and if so in what amounts will depend on the winds and turbulence between the release point and the target. In some cases the means for measuring and forecasting these winds in real-time is very limited and thus is another source of uncertainty. Some seeding particles from ground-based generators could be scavenged by snow and ice and therefore diminish the effects of seeding (Warburton et al., 1995). For all of these reasons the targeting and mixing of the seeding material through a cloud remains highly uncertain. However, with new high-resolution mesoscale numerical models and remote sensors, new opportunities exist to address these issues, especially in winter orographic situations. In-cloud and cloud-top seeding introduces similar uncertainties but could also potentially be addressed with new modeling and observational tools.

The physical processes that lead to precipitation development are very complex and depend, among other things, on the number and characteristics of aerosol particles in the cloud-forming air. The atmosphere contains a tremendous amount of particulate matter from a wide variety of natural and anthropogenic sources. These include, for example, soot, sea salt, volcanic ash, wind-blown sand and dust, biogenically-derived materials such as pollens and spores, and a variety of sulfur, nitrogen, and carbon compounds (which often result from industrial pollution, biomass burning, and other combustion processes). Soluble and hydrophilic particles absorb water and can eventually act as CCN. Some insoluble particles with wettable surfaces may adsorb water and serve as large cloud drop nuclei or ice nuclei. Some insoluble particles have a crystalline structure that provides an efficient starting place for ice crystals to grow and thus are referred to as ice nuclei (IN); the exact composition of most IN is not well known. Differences in the initial population of atmospheric aerosols affect the cloud particle and cloud drop populations, which subsequently affect the amount of precipitation reaching the ground.

To fully evaluate the utility of glaciogenic cloud-seeding agents requires a more complete understanding of natural ice formation processes. Measurements are needed of the origin of natural ice nuclei, what their composition is, how they act in clouds, and how they are distributed in the atmosphere. The impacts of changes and variability in engineered and natural aerosols on ice formation must also be investigated, so that their impacts on cloud modification efforts can be understood and even anticipated. Instruments that measure ice nuclei and/or ice crystal concentrations could provide this information.

To date, there have been few programs with a research component to verify the efficacy of this seeding protocol. Such research could potentially benefit many programs - by revealing the influences of local circulations, recommendations could be made to enhance operational seeding procedures by identifying optimal locations for seeding equipment and optimizing the use of aircraft and existing seeding equipment.

9.1.3 Statistical Evidence

To have reasonable confidence in the results of seeding experiments they must be carefully designed, conducted, and analyzed with the best techniques available. The goal is to minimize uncertainties resulting from the large variability in natural weather systems, from our incomplete knowledge of the physical processes involved, from our limited ability to measure the relevant meteorological variables and to target seeding agents, and from our inability to replicate experiments (in the strictest sense of the word).

Assessments of seeding effects most often consist of comparisons of the amount of precipitation (e.g., rain) measured in a target area with that from a control area. Many of these comparisons, especially in the early days of seeding, did not involve randomization. The target and control areas often were the same fixed geographical area, and comparisons were between measurements made during the seeding period and those from a period without seeding. Alternatively, the control area might be a geographically fixed area adjacent to (and meteorologically similar to) the target area. In this case, comparisons are made between measurements from the two areas during the same time periods. In either of these designs the comparisons are usually discounted because there is no way to allow for biases arising from temporal or spatial trends that may have been present during the trial period. A more statistically robust design, known as a cross-over, uses two similar fixed areas. During each test case one area is selected for treatment through a random process while the other serves as the control.

Statistical evaluation has usually taken the form of randomized seeding experiments (see section 4) or comparing target and control area precipitation amounts using either snow or precipitation gauges.

Statisticians working with meteorologists have developed a range of design and analysis techniques for assessing seeding experiments. In addition to randomization and replication, a well-designed weather modification experiment may include pre-screening or blocking to reduce the variance in the test group, use of covariates, alternating target and control areas (cross-over design), and re-randomization as a means of coping with internal variance and small sample sizes. Classical hypothesis testing often is replaced by a comprehensive data analysis in which all of the measured variables are brought to bear on the question of seeding effects (Gabriel, 1979; Flueck, 1971). Another relatively new statistical method that may provide even better evaluation capabilities is the Bayesian technique, which can explicitly account for sources of uncertainty and complicated spatial and temporal dependencies. This technique could have major impacts on weather modification research if utilized.

9.2   Proposed Evaluation Methodology for Wyoming

9.2.1   Physical Evaluation

The general seeding conceptual model for winter orographic clouds can be summarized in microphysical terms as follows:
1. Silver iodide (seeded) particles in supercooled liquid water regions of the clouds result in enhanced concentrations of ice crystals by either nucleating new crystals or freezing cloud droplets.
2. These enhanced concentrations of ice crystals will grow by vapor deposition at the expense of cloud droplets in the region until they are large enough to start collecting cloud droplets (riming) and/or aggregate with other ice crystals to form snow particles.

3. This will result in higher concentrations of rimed ice crystals (graupel particles) and aggregates (snow particles).
4. These enhanced concentrations of graupel and/or snow particles will then precipitate to the ground resulting in more precipitation at the ground.

This effectiveness of this sequence of events will depend on how well the seeding material is targeted and dispersed from both ground-based generators and the aircraft. However, with the aircraft, targeting should be less of an issue. The enhancement of ice crystal concentrations will depend on the natural background concentrations of ice crystals which in turn is dependent on natural ice nuclei (IN) concentrations. The riming characteristics will depend on the cloud droplet spectra which depend on the natural cloud condensation nuclei (CCN) in the atmosphere. Based on the natural concentrations of CCN and IN, the seeding effects may be quite variable in terms of precipitation at the ground. Based on the measurements described in section 3 there is still some uncertainty on what the natural levels of CCN and IN are. Therefore it is quite prudent to have a physical evaluation component to the program to evaluate these natural concentrations and their effects on seeding operations.

9.2.2   New Equipment for Physical Evaluation

Aircraft
An instrumented research aircraft that could be used simultaneously for cloud seeding and physical measurements would be desirable during the first year of a potential program. The proposed instrumentation package for the aircraft would be as follows:
  – Particle Metrics, Inc. [PMI] Forward Scattering Spectrometer Probe [FSSP] (able to detect cloud droplets between 2 and 47 µm diameter) or similar probe
  – PMI Passive Cavity Aerosol Spectrometer Probe [PCASP] (able to measure concentrations and sizes of aerosol particles between 0.1 and 3.0 µm diameter)
  – PMI 2D-C Optical Array Imaging Probe (able to detect cloud and precipitation particles between 25 to 800 µm diameter) or similar probe
  – PMI 2D-P Optical Array Imaging Probe or a SPEC High Volume Particle Spectrometer [HVPS] (able to detect cloud and precipitation particles between 0.1 to greater than 6.4 mm diameter)
  – Cloud Liquid Water (CLW) sensor
  – Cloud Condensation Nuclei (CCN) counter
  – Condensation Nucleus (CN) counter
  – Ice nucleus (IN) counter
  – System to measure three-dimensional wind components
  – Temperature, pressure and dew point sensors
  – Data recording system with telemetry

This instrument package has been designed such that all parameters related to evaluating the seeding potential for winter orographic clouds could be assessed. The measurements will be used to identify natural ice nuclei, cloud condensation nuclei, ice crystal concentrations, cloud liquid water content regions and the time evolution of these regions. In addition, the instruments will be used to characterize the local thermodynamic structure of the atmosphere in which clouds develop. Digital cameras will be used to record flight conditions. The aircraft will also be equipped with silver iodide flares.

The effects of glaciogenic seeding are highly dependent on the natural characteristics of clouds and precipitation processes. Very few measurements of the microphysical processes in clouds

in the Wind River region from past experiments are available. These physical measurements are therefore important in order to assess which seeding technique should be used and to evaluate the potential effects from seeding on precipitation. This will also involve understanding the physical chain of events of seeding and hence assessing the impacts of seeding to enhance precipitation. In addition, aircraft measurements of cloud microphysical characteristics will provide a better understanding of the natural processes in clouds in the region. The aircraft data are important to build climatology of microphysical characteristics of clouds in the region to determine the dominant precipitation formation processes in clouds and the effects seeding may have on these processes. These measurements will also help to validate the model simulations and radar observations. A strategy for airborne flight patterns for data gathering to answer important questions related to the natural and seeded characteristics of clouds should be developed prior to such an experiment.

Polarimetric Radar

The National Weather Service is currently planning to upgrade the national network of WSR-88D radars with polarimetric capability. This capability will significantly enhance the utility of the radars in orographic precipitation events and their ability to evaluate cloud seeding programs. It is therefore suggested that the State of Wyoming attempt to speedup the upgrade on the Wyoming WSR-88D's before the start of a program. This will significantly enhance the capabilities to quantify and evaluate seeding effects.

Rain rate and snow estimation from radar measurements is based on empirical models that are usually derived from regression analysis of radar reflectivity and rain gauge measurements or numerical simulations. In the case of polarization radar, additional observables such as differential reflectivity (Z_{DR}) and specific propagation phase (K_{DP}) are included in the empirical models. Accuracy of radar-based rain rate estimation is limited by non-linearity in empirical models. Accuracy in radar-based rain rate estimation can be improved by a better description of raindrop size distributions (DSD) and distinguishing between liquid and solid precipitation. For example, a Gamma DSD with three parameters is capable of describing a broader variation in raindrop size distribution than an exponential function. Reflectivity, Z_{DR} and a relation based on video disdrometer observations are used for retrieving rain DSD. Besides accurate rain rate estimation, spatial variation in rain DSD allow better understanding of evaluation of raindrop spectra. Spatial variations in rain DSD are compared with precipitation particle classification results. Self-consistency among Z, Z_{DR} and K_{DP} is used for evaluating DSD-based precipitation estimates.

Polarization-diversity (dual-polarization) radars measure signals backscattered from targets in two orthogonal orientations to discriminate between water and ice in clouds, detect hail, identify the types of particles present, and attain more accurate estimates of rainfall rates using differential phase (K_{DP}) methods (Bringi and Chandrasekar, 2001). These capabilities are of great potential value in assessing cloud-seeding experiments. For individual cloud studies, polarimetric particle classifications have the potential to reveal the transformation of supercooled liquid water droplets to ice crystals in glaciogenic seeding and the development of large drops in hygroscopic seeding. They can also follow the movement and dispersion of seeding aerosols using microwave chaff fibers as tracers. Three-dimensional depictions of these processes may be observed as they occur, using ground-based polarimetric radars. The particle classifications also can refine conventional reflectivity-based rainfall estimates by identifying regions of echo that are not rain or contain rain with contaminations of hail, snow, ground clutter, or insects. The new differential phase estimation of rainfall rate offers a method for measuring the ground-level result of seeding that is free from several factors that have

historically degraded the simple reflectivity-based estimates of precipitation. The method avoids or minimizes problems related to hardware calibration errors, attenuation, partial beam filling, partial beam blockage, the presence of hail, and variability of drop size distributions.

Dual polarization radar is highly recommended because rain/snow rate estimates are relatively immune to any bias and rainfall can be estimated by more than one technique. Dual-polarization measurements can also be used for detecting clutter, anomalous propagation and artifacts in radar measurements. Thus, it is easier to perform quality control on dual-polarization radar measurements. Furthermore, the polarimetric particle identification also would allow new research in cloud physics for cloud seeding to be done. The hydrometeors in cloud and around any precipitation storm can be identified so that likely areas for successful seeding can be performed and assessed. The assimilation of radar data into numerical models during seeding episodes could also substantially enhance the ability to identify regions in clouds that are seedable and increase the predictive skills of the model. The NCAR TITAN/CIDD/REC software systems could also be very helpful for guiding and evaluating the seeding experiments. This could be added at the Operations Center.

The advantages of the upgraded polarimetric radar can be summarized as follows:
- More accurate precipitation measurements.
- Physical measurements to support randomized seeding experiment.
- Measurements to help understand seeding effects and quantify the results.
- More accurate rainfall measurements beneficial for hydro-meteorological studies.
- More easily compared to and combined with aircraft measurements for understanding and supporting seeding.
- Detect differences in raindrop size distributions between seeded and unseeded clouds.
- Precipitation products, such as rain rate and liquid vs. ice detection.
- Assimilation of radar data into numerical mesoscale models.

With the capability of classifying particle types it would be possible to track the seeding effects in real-time and provide for much better post-program evaluation of seeding effects. The Radar Echo Classifier can also identify different type radar echoes for ease in operations use. For example, the REC can classify precipitation echoes and separate them from artifacts as AP ground clutter, clear air echoes, sea clutter, etc.

The cost for the upgrade of the WSR-88D radars is already included in the NWS budget. The lease of the NCAR software programs for the evaluation would cost approximately US$38,000 per year.

Microwave Radiometer
Microwave radiometers have developed significantly in the past ten years and are used in many operational and research winter orographic cloud seeding experiments. They provide valuable information about several parameters in the atmosphere and are now available in both azimuth and elevation scanning modes.

The Radiometrics TP/WVP-3000 Temperature, Humidity and Cloud Liquid Profiler (Fig. 9.1) provides continuous temperature and humidity profiles to 10 km height, and a one-layer cloud liquid profile. The radiometer is easy to use, accurate, reliable and portable. It is a passive instrument that does not emit radiation. Atmospheric profiles can be obtained at 20 sec intervals during clear, cloudy, and precipitating conditions.

The radiometer includes two independent receivers in the same cabinet that share the antenna and pointing system. The water vapor profiling (WVP) and temperature profiling (TP) systems observe at selected frequencies in the 22 – 30 GHz band and 51 – 59 GHz band. The radiometer system also measures cloud base temperature and surface pressure, temperature, and humidity.

Figure 9.1 – Radiometrics microwave radiometer

Statistical comparisons of co-temporal radiometric and radiosonde soundings demonstrate that the two methods are roughly equivalent in accuracy when used for numerical weather analysis. However, current radiometric upper air measurements can be an order of magnitude more accurate than radiosonde soundings with 12 hour latency.

A Rain Effect Mitigation system is included that minimizes water film on the radiometer radome, providing for operations during nearly all weather conditions. A transportable aluminum telescoping tripod is included. Elevation scanning is also included, and optional azimuthal pointing capability is offered. Specifications are listed in Table 9.1, below.

Table 9.1 - Radiometrics Microwave Radiometer Specifications

Observation Cycle Time (configurable)	10 sec to 10 min
Accuracy	0.5° C
Resolution	0.25° C

Surface Measurement Accuracy
    Temperature
    Relative Humidity
    Barometric Pressure
	
	0.5° C
	2%
	0.3 mb

Operating Temperature	-50° C to +50° C
Power	200 watts maximum
Voltage	90 to 250 V (47 to 63 Hz)
Dimensions	50 x 28 x 76 cm

Weight	32 kg
Angular Coverage	All sky with optional azimuth scanner

A laptop computer with Neural Network retrieval software for customer selected sites is included with the TP/WVP-3000. Reusable shipping containers are also included.

VizMet software that displays real time radiometric observations is provided with the TP/WVP-3000. This Windows software provides flexible temperature, humidity and liquid contour displays, and comparisons with radiosonde soundings. Example VizMet displays are shown in Figures 9.2 and 9.3.
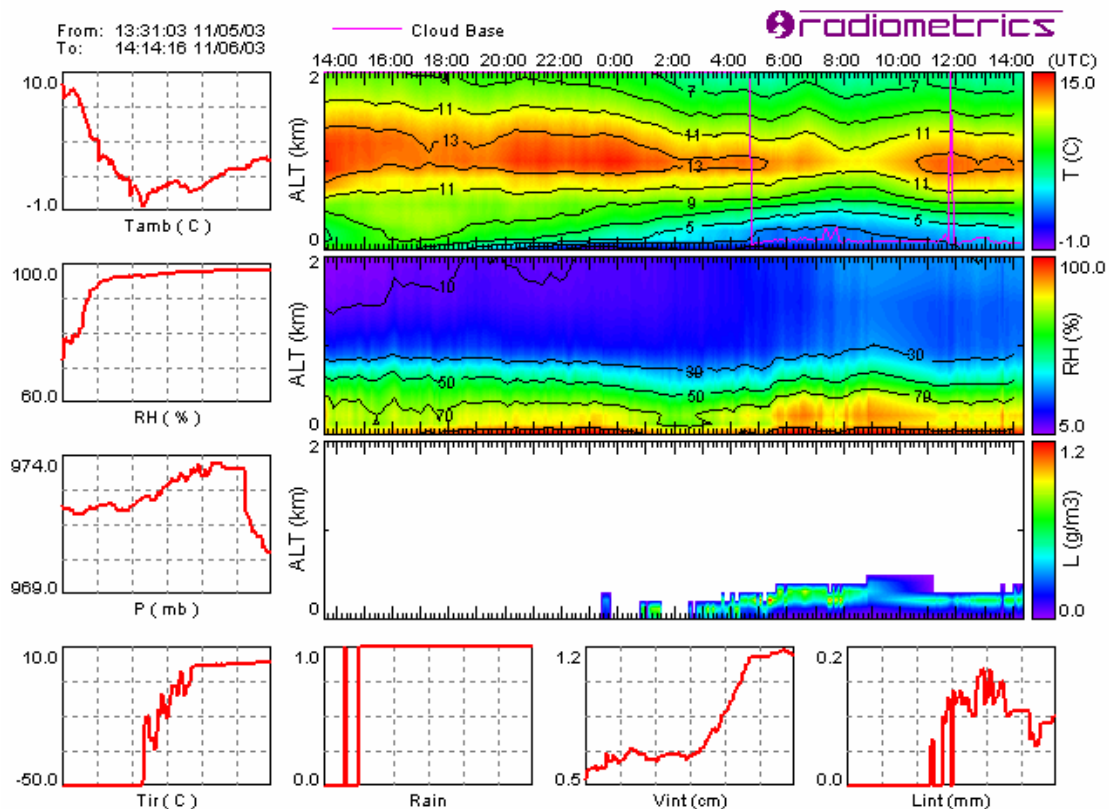
Figure 9.2 - VizMet display of TP/WVP-3000 observations on 5-6 November 2003 during the COST 720 International Temperature, Humidity and Cloud Profiling Experiment at Payerne, Switzerland. Radiometer data were provided by the U.K. Met Office.

The microwave radiometer could identify cloud liquid water regions in both upslope and gravity wave cloud conditions and act as a validation tool for the numerical model simulations. It would be valuable in guiding seeding operations with both the ground-based generators and the aircraft. In addition, the inclusion of these data into numerical models could provide for greatly enhanced model predictions. Vertical temperature and humidity profiles could be obtained much more frequently than is available with rawinsondes which are only launched twice a day. The lease cost of the radiometer for a 4.5-month field effort will be approximately US$50,000.
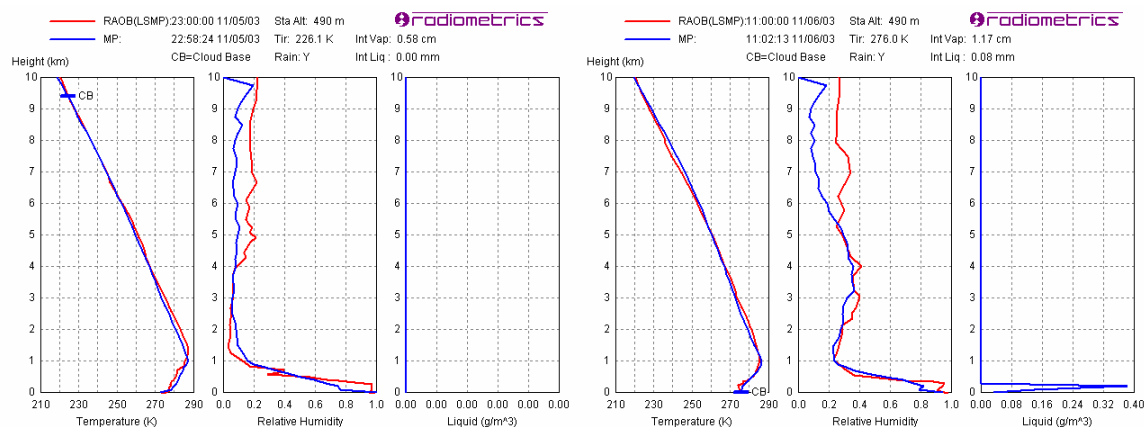
Figure 9.3 - VizMet display of co-temporal radiometer and radiosonde profiles at 2300 UTC 5 Nov and 1100 UTC 6 Nov 2003. A temperature inversion near 1 km height, relative humidity saturation below 400 m height, and fog after 2300 UTC 5 Nov is seen.

9.2.3   Physical Evaluation Using Numerical Modeling

The model simulations may be used in the scientific evaluation of cloud and precipitation formation specific to the region. The objectives of the numerical model experiments are (1) to simulate the formation of clouds over the complex terrain in the region, and (2) to study detailed effects of seeding using more detailed numerical models. Different events would be selected that are common during precipitation periods in the region to determine the spatial distribution of clouds and rain/snow over the region and to determine what role the mountains and other surface characteristics play in the spatial and temporal distribution of precipitation. The simulations will preferably be conducted using events during the field effort. The simulations will then be conducted on the natural case and separately to include seeding. These simulations will then be compared to identify differences in precipitation between the two simulations as well as compared to the observations. The comparisons should provide an indication of any potential increases due to seeding. Several parameters in the model could also be varied to investigate the effects of seeding for different natural conditions, such as changes in IN and CCN. The costs associated with these evaluations will be approximately US$60,000 per year (depending on the number of cases to simulate – this assumes 4 or 5 well documented cases).

9.2.4   Statistical Evaluation

There are several possibilities in designing a statistical seeding experiment for winter orographic clouds and no one approach is by itself satisfactory. Obviously, a target area or entity needs to be established or defined, and the statistical evaluation then focuses on precipitation in the target. Comparisons to determine seeding effects can involve: 1) historical regression techniques, using long-term precipitation records; 2) randomization – seeding or not seeding the target; 3) control areas or entities, chosen for their high correlation to the target; 4) crossover methods which alternate between treating control and target areas; 5) floating targets and even floating controls; and other combinations or variations of these methods.

Based on the results of past experiments and the ability to collect increasingly more physical measurements, a preliminary evaluation method is proposed that uses established (but often inconclusive) methods for initial guidance and background on precipitation in the region, and measurements along with numerical modeling to establish the plausibility of the seeding

operations and any potential seeding effects. Aspects of this technique were employed by the Denver Water Board in evaluating their cloud seeding activities (http://www.water.denver.co.gov/cloudseeding_summary.html) and a more research oriented approach using the same ideas is being used in a project in the Puglia region of Italy.

The veracity of the numerical model used for evaluation would be established through the case studies of the physical evaluation (mentioned above) as well as through additional measurements that could verify the precipitation patterns and the extent of the seeding (i.e., tracers, silver content analysis, etc.). An exciting addition to the evaluation method that the numerical model brings is detailed time-dependent position of the seeding plume. This allows a number of options for determining the target area, which will have to be further investigated in developing a final design.

Some of areas of investigation could include: 1) the use of polarimetric radar data in conjunction with SNOTEL data in defining area extent of precipitation affected by seeding, as well as not affected (control areas); 2) time-dependence of seeding plumes in defining target and control areas; 3) identification of CLW regions in determining target/control areas; 4) the potential for randomization by storm event, by individual seeding generator, or by some combination involving both generators and time.

The statistical evaluation is intimately tied to the physical evaluation and measurements, which in turn are verifying the conceptual model of seeding. The final design should therefore address all aspects (seeding operations effectiveness, physical responses, and precipitation on the ground) of a program in the evaluation effort. The importance of the numerical modeling work in both designing and evaluating the seeding program requires a substantial effort in order to most effectively apply the model to this problem. Estimated cost for this effort is US$100,000 annually.

10. HYDROLOGIC ASSESSMENT

10.1 Potential Benefiting Sectors

An important issue in any precipitation enhancement program is the determination of the potential benefiting sectors. Winter cloud seeding to increase snowfall in mountainous areas is designed primarily to increase runoff for hydroelectricity and water supplies for lower, semi-arid elevations.

On the west side of the Wind River Range crest line, which is also the continental divide, lies the Green River that flows south into Utah. The 1922 Colorado River Compact established the upper and lower Colorado River sub-basins, of which Wyoming is part of the upper basin. A 1948 upper basin compact between Colorado, Utah, New Mexico, and Wyoming established Wyoming's share as 14% of the upper basin allocation. Currently, Wyoming's annual allotment is 833,000 ac-ft, for use in the Little Snake and Green River basins. Tributaries to the Green include the New Fork, Big Sandy, and Black Fork. The water from the Wind Rivers is stored in a number of lakes and reservoirs, on the flanks of the Wind Rivers themselves. Further south, the Green River flows into and is stored in the Fontenelle Reservoir. At the south end of Fontenelle Reservoir is Fontenelle Dam and power plant located 24 miles southeast of La Barge. The power plant generating capacity ranges from 1,000 kW at minimum flows to 11,000 kW at maximum flows during spring runoff. The reservoir has a surface area of 8,000 acres at an elevation of about 6,500 feet. The lake is 20 miles long when full and has a shoreline of about 56 miles. Recreation management at Fontenelle Reservoir is performed by the Bureau of Land Management (BLM) by arrangement with the U.S. Bureau of Reclamation (USBR). Stream fishing opportunities also exist on the Green River above and below the reservoir. Below Fontenelle Dam and south of Interstate 80 and the City of Green River, the Green River fills Flaming Gorge Reservoir. The reservoir has a total capacity of 3,788,900 acre-feet. At full elevation of 6,045 feet, it has a surface area of 42,020 acres. The power plant at Flaming Gorge Dam has a peak capacity about fifteen times that of Fontenelle power plant containing three 50,650 kW generators.

On the east side of the continental divide, waters flow into the Wind River, this eventually bends northward and flows into the Big Horn River. The Big Horn River in turn joins the Yellowstone in south-central Montana. The confluence of the Yellowstone and Missouri Rivers occur in extreme northwest North Dakota. The Yellowstone River Compact of 1950 allocated 80% of the Bighorn River flow to Wyoming. This arrangement provides for significant water available for consumptive uses in Wyoming when the Bighorn River discharges the average-year flow of 3.9 million ac-ft. In 1977, the Wind River Indian Reservation was awarded 500,000 ac-ft of reserved water rights of the Wyoming rights. The method used to mitigate the low discharge impacts of dry years is storage of water. Local water storage facilities and lakes on the east side of the Wind Rivers are lesser in size and number but include Bull Lake and a few others to the north. Further downstream, Boysen Dam near Thermopolis, Wyoming, forms a significant reservoir. The Boysen power plant contains a pair of 7,500 kW generators for a total capacity of 15,000 kW. Boysen Reservoir offers fishing year round. Fish species include Trout, Walleye, Perch and Ling. The reservoir typically has about 20,000 surface acres and 77 miles of shoreline. The recent drought has highlighted the need for additional storage within the headwaters of Wind/Bighorn River basins. These are currently being considered the WWDC.

The primary drainage of Medicine Bow/Sierra Madre target area is provided by the North Platte River Basin, which is the most densely populated basin in the state. The North Platte originates

in the mountains of Colorado, flows north towards Casper, Wyoming, then eventually flows southeastward into Nebraska. The tributaries include Encampment, Sweetwater, Medicine Bow, and Laramie. Several reservoirs, managed by the U.S. Bureau of Reclamation, have a combined capacity of over 3 million ac-ft. The North Platte River is considered to be fully allocated. Wyoming depletes approximately 800,000 ac-ft of North Platte River Basin surface flows. Downstream obligations have depleted these storage facilities during the recent drought.

The Medicine Bow feeds the Seminoe, Pathfinder and Alcova Reservoirs prior to turning east near Casper. From there, the North Platte continues to Douglas where it wends its way south feeding Glendo Reservoir before leaving the state near Torrington. Seminoe Dam, this first on the series, is part of the Kendrick Project. Its purpose is to conserve the waters of the North Platte River for irrigation and electric power generation. The project is a multi-purpose development with storage at Seminoe Reservoir and diversion at Alcova Dam to project lands. Seminoe Reservoir, with a total capacity of 1,017,279 acre-feet, provides storage capacity for the water to irrigate the project lands. The power plant generates up to 51,750 kW as the water is released for irrigation or stored in Pathfinder Reservoir for later release as required. Water from Alcova Dam is released to satisfy other irrigation rights downstream through the Alcova Power plant or over a controlled spillway. The plant uses the 165-foot drop from the reservoir to the river for power generation. It consists of two units, each a 20,700 kW generator driven by a 26,500-horsepower turbine. The reservoir has a total capacity of 184,208 acre-feet of which only the top 30,606 acre-feet is active capacity available for irrigation.

The Glendo reservoir and dam is a multi-purpose project furnishing a maximum of 40,000 acre-feet of water annually from Glendo Reservoir for irrigation in Wyoming and Nebraska. Glendo and Fremont Canyon power plants supply electrical power to Wyoming, Colorado, and Nebraska. The Glendo unit provides irrigation, power generation, flood control, fish and wildlife enhancement, recreation, sediment retention and pollution abatement. It also improves the quality of municipal and industrial water supply in the North Platte River Valley between Gray Reef Dam and Glendo Reservoir. The addition of the Glendo power generation facilities increases available power in the North Platte River Basin by about 500 million kilowatt-hours annually. This increase comes principally from the Glendo and Fremont Canyon power plants; however, some of the gain is due to the conversion of the Alcova power plant from seasonal to year-round operation made possible by the flood control afforded by Glendo Reservoir.

10.2   Potential Increases in Precipitation

A literature search shows there have been no quantitative studies assessing cloud seeding experiments in Wyoming in the past and thus no quantitative studies relating cloud seeding and runoff and/or groundwater. Therefore, we will use data from other cloud seeding experiments and hydrological related studies to make a preliminary assessment of potential hydrological impacts of a cloud seeding experiment in either the Wind River or Medicine Bow/Sierra Madre Mountain Ranges.

As was discussed in the previous sections and also quoted in statements by professional organizations such as the American Meteorological Society, it is generally accepted that winter orographic cloud seeding experiments have provided the most convincing data to date that cloud seeding could enhance precipitation, especially snowpack in mountainous terrain. This was also quoted by the recent National Research Council of the National Academies report (NRC, 2003).

Winter orographic snowpack enhancement programs have generally shown that precipitation could be enhanced anywhere from 10 to 20 percent. There is a broad body of evidence in the literature and in company reports describing the results from various operational and research projects involving winter orographic clouds. Some of these projects are cited in Table 10.1.

10.3   Potential Water Resources Impacts

Studies of rain enhancement programs in North Dakota report up to a 15 percent increase in rainfall (Johnson, 1985) and up to a 5.9 percent increase in wheat yields (Smith et al., 1992). Indirect qualitative assessments of the additional water produced from the Utah operational programs described by Griffith (1991) indicated costs in the range of a few dollars per acre-foot (Stauffer and Williams, 2000). The Tasmanian program calculated a cost-benefit ratio of 13 to 1 (Ryan and King, 1997). These results are viewed as beneficial for hydropower energy production (Cotton and Pielke, 1995).

Table 10.1 - Examples of winter orographic snowpack enhancement programs and results

Name	Location	Seeding Method	Random- ized	Results/Confidence
Jemez	Jemez Mountains Northern NM.	Ground	Yes	13% increase*
Tasmania	Tasmania	Air	Yes	10-15% increase*
Climax I & II	Climax, CO	Ground	Yes	13-24% increase*
Israel I	Israel	Air	Yes	15-22% increase*
Israel II	Israel	Air	Yes	13-18% increase*
Utah Winter Program	Central & Southern Utah	Ground	No	11-15% increase
Boise River Drainage	Boise, Idaho	Ground	No	12% increase

*This result was significant at the 95% confidence level

In preliminary calculations in northern Texas, it was found that – based on a certain increase in precipitation from cloud seeding and calculating the cost of the additional water – a 1 ac-ft of water from cloud seeding costs between 70 and 80 cents per ac-ft with a cost benefit ratio of more than 100:1. Studies in New Mexico during drought conditions in an Upper Rio Grande study indicated that a 10 percent decrease in precipitation led to a 30 percent decrease in stream runoff. The time to fill a reservoir during periods of average precipitation was 3.5 years; with a 10 percent decrease in precipitation, it would take 14 years to fill the same reservoir. A winter seeding program in the Jemez Mountains by New Mexico State University (NMSU) in 1968-1972 reported a 13 percent increase in precipitation from the clouds which were seeded and estimated that, had they seeded all the clouds, they would have produced a 28 percent increase in precipitation. It was calculated that a 10 percent increase in precipitation (snowpack) resulted in at least 20,000 ac-ft per year in runoff. They calculated that an initial program cost of approximately $700,000 would result in a cost of about $35 per ac-ft which for them would result in a benefit/cost ratio of 28:1 assuming the value of one acre foot is $100.

However, it must be emphasized that estimates of this nature vary from one project to the other and that some of the evaluations have not been verified by independent entities. However, these calculations show that cost benefit ratios vary from 5 to 1 to close to 100 to 1. In general, all calculations have indicated that cloud seeding could potentially be a very competitive alternative for additional water resources.

To study the effects on water at the surface and sub-surface, such as river flows, reservoir and ground water levels, a study in South Africa (Howard and Gorgens, 1994) showed that the

average increase in mean annual rainfall due to seeding over a specific catchment was 32 percent. The increase in reservoir levels for a mean annual rainfall resulted in an average value of 27 percent (including net reservoir evaporation losses). The range in median increases was 20 to 48 percent for mean annual rainfall and 14 to 42 percent for reservoir yield. Simulations showed that the average median timber yield increase due to seeding was 22 percent. These results were based on data from a randomized cloud seeding experiment in South Africa using Silver Iodide and dry ice seeding material showing a 10 percent increase in rainfall from individual convective storms due to seeding. However, the results from the hygroscopic seeding experiments conducted during the early 1990s in South Africa indicate an even larger increase in mean annual rainfall. Gorgens and Jewitt (1995) calculated the unit cost of augmentation and found that it was remarkably competitive with other options for providing additional water resources.

It is important to note that the relationship between increases in snowpack and runoff may not be a linear relationship as studies above have indicated and that potential benefits may go beyond runoff and also affect ecosystems, groundwater levels and possibly glaciers as mentioned in Section 3. Issues such as time-of-year, large-scale forcing and other climatological attributes can impact the amount of runoff achieved from the snowpack. For example, the loss of snow mass from sublimation either through direct radiative forcing (solar), thermal forcing (warm, dry wind), or from blowing snow dynamics is a critical part of basin scale water budgets in snow dominated regions. In exposed landcover regions such as prairie and tundra, estimates of sublimation loss of blowing snow can be 15-41% of annual snowfall. Likewise, estimates are that one-third of total snowfall falling on spruce and pine can be lost through canopy sublimation (Pomeroy and Gray 1995). Observational evidence in snow dominated watersheds in Colorado, for example, have shown that sublimation losses can vary from year-to-year depending on weather conditions (e.g. spring days with clear skies and warm winds will lead to substantially more sublimation loss than cloudy days and still winds during the same time of year). A recent study by Boyle et. al (2005) suggest the runoff achieved from snowpack during the 2003-2004 winter season in the Walker River Basin, on the eastern side of the Sierra Nevada just north of Yosemite National Forest, varied between 65% to over 90% of the snowpack snow water equivalent. For purposes of this study, an estimate of 80% runoff achieved from the snowpack will be used. Additional studies will be necessary to assess these relationships for the Wind River and Medicine Bow Mountain Ranges.

10.4   Potential Impacts on Both Target Areas

The challenge of studying the non-linear feedback between increases in snowpack due to seeding operations and the ensuing runoff is a sizable task that requires both atmospheric and hydrology-based modeling. Reliable results would take months and possibly years to achieve. In the interim, an estimate based on results in Section 10.3 of 8 percent increase in runoff due to a 10 percent increase in snowpack from a successful seeding program will be used in this section. Runoff data was obtained from the US Geological Survey (USGS) website for Wyoming located at: http://nwis.waterdata.usgs.gov/nwis. Figure 10.1 and 10.2 show the gages used in this analysis and the sub-basins they represent. Table 10.2 provides details of the selected gaging stations.

Annual runoff data from the USGS site represents the total amount of water that flowed past a given streamflow gaging station. Gaging stations around the Wind River Range are numerous and it was possible to build a series of sub-basins that cover a majority of this area of interest. Many of these gages are still active today. In contrast, the Medicine Bow and Sierra Madre

ranges have fewer current gages available for use and thus the historical records had to be accessed to provide a reasonable estimate. In order to represent target areas that may be impacted by significant snowpack increases, basins were selected for use if at least half the stream origins occur within the National Forest areas within the range.

The site monthly averages, in units of cubic feet per second, were obtained from the USGS website for the period of record for each gaging station. These averages were converted in acre feet based on the number of days in the month using the equation:

Runoff (in ac-ft) = Runoff (in ft^3/s) * 1.983 * number of days

Wind River Mountains
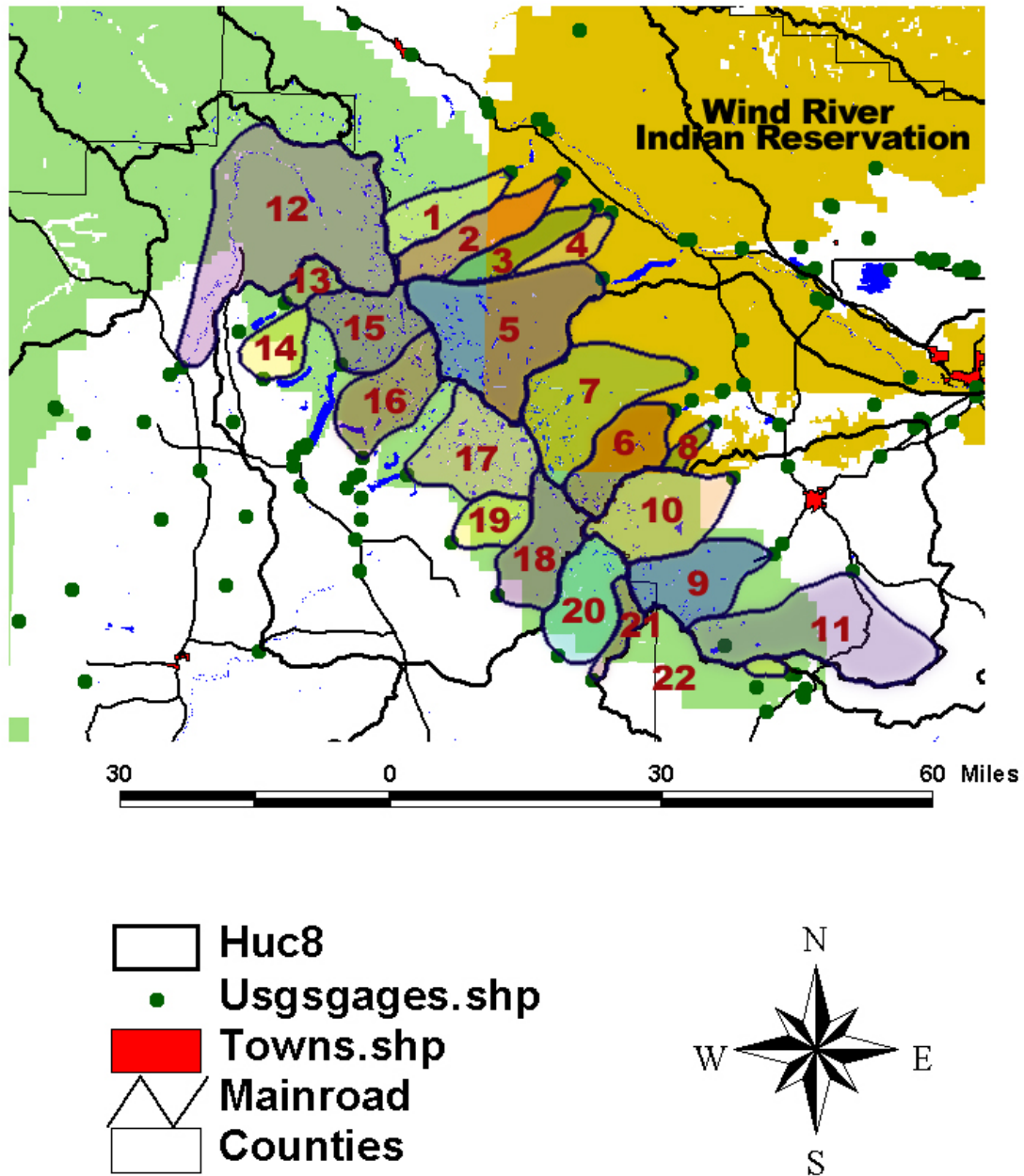
Figure 10.1 – Location of gages and sub-basins in the Wind River Range. Numbers correspond to information provided in Table 10.2. (Source: Bruce Brinkman, WWDC).

Sierra Madre and Medicine Bow Mountains
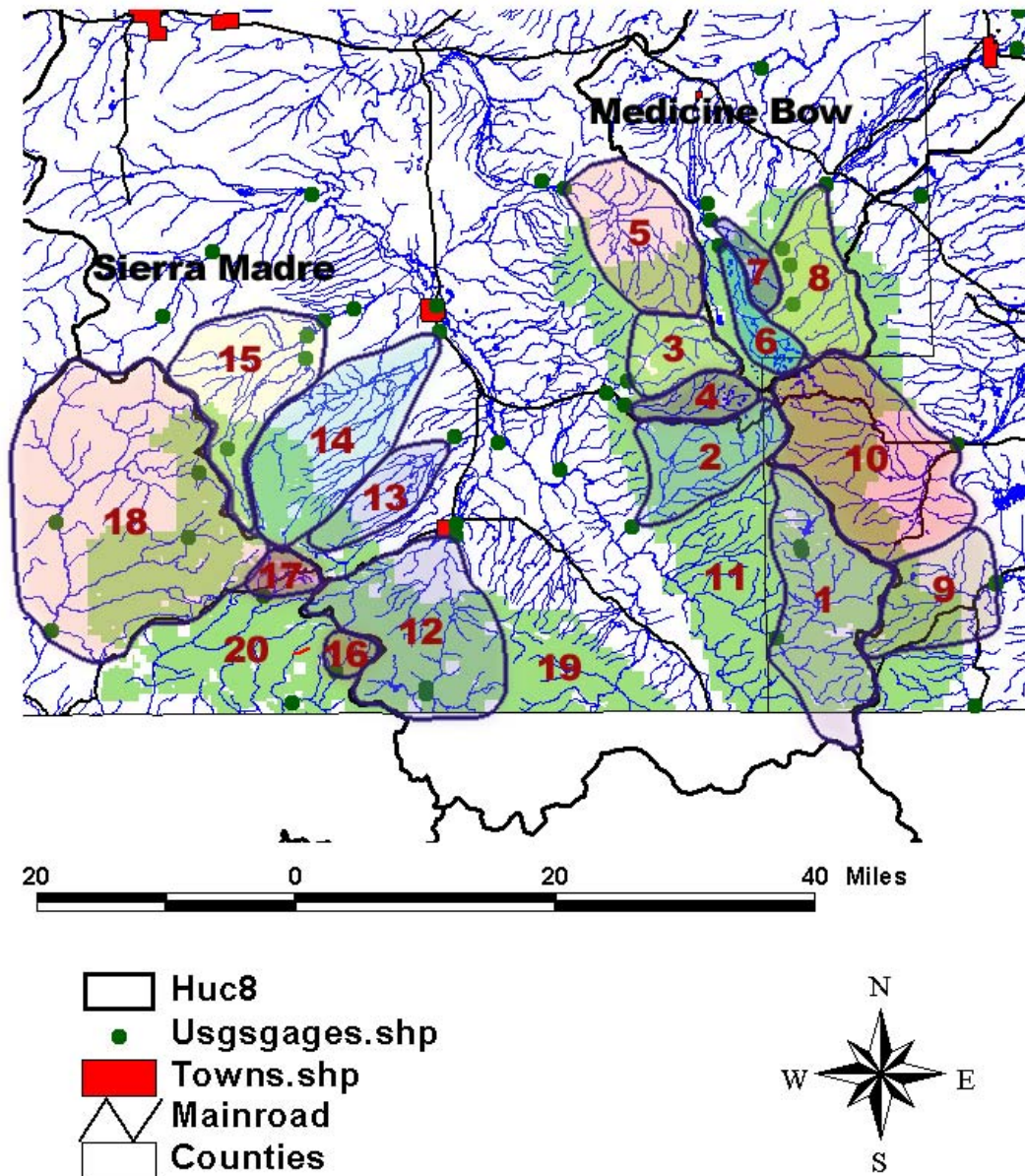
Figure 10.2 – Location of gages and sub-basins in the Medicine Bow/Sierra Madre Ranges. Numbers correspond to information provided in Table 10.2. (Source: Bruce Brinkman, WWDC).

Table 10.2 - Summary of gaging stations and sub-basins in the Wind River Range and the Medicine Bow/Sierra Madre Ranges shown in Figures 10.1 and 10.2.

Area Number (shown in Figure), Stream Gage Location and WY population center the gage is near	USGS Station Identifier	Drainage Area (sq. mi)	Period of Record Utilized
Wind River Range			
1. Dinwoody Creek near Burris	06221400	88.2	1958-present
2. Dry Creek near Burris	06222500	53.7	1922-1940, 1988-present
3. Meadow Creek near Lenore	06223000	41.7	1922-1923
4. Willow Creak near Crowheart	06223500	55.4	1921-1922, 1925-1940, 1988-present
5. Bull Lake Creek above Bull Lake	06224000	187.0	1941-1953, 1966-present
6. SFk Little Wind R. above Washakie Res.	06228350	90.3	1976-present
7. NFk Little Wind River near Fort Washakie	06228800	112.0	1988-present
8. Trout Creek near Fort Washakie	06229900	16.1	1990-present
9. Middle Popo Agie River near Lander	06231500	86.5	1911-1912, 1918-1924
10. North Popo Agie River near Milford	06232000	98.4	1945-1963
11. Little Popo Agie River near Lander	06233000	125.0	1946-present
12. Green River near Daniel	09188500	468.0	1931-present
13. New Fork River above New Fork Lakes	09192750	21.8	1985
14. Willow Creak near Cora	09194500	41.8	1938-1941
15. Pine Creek above Fremont Lake	09196500	75.8	1954-1997
16. Pole Creek near Pinedale	09198500	87.5	1939-1971
17. Boulder Creek near Boulder	09201500	115.0	1938-1939
18. East Fork River near Big Sandy	09203000	79.2	1938-1992
19. Silver Creek near Big Sandy	09204000	45.4	1939-1971
20. Big Sandy River at Leckie Ranch	09212500	94.0	1939-1987
21. Little Sandy Creek near Elkhorn	09214000	20.9	1939-1971
22. Non-gaged area on S side	Covered by over-estimate provided by 06233000		
Medicine Bow Range			
1. Douglas Creek near Foxpark	06621000	120.0	1946-1971
2. French Creek near French	06622500	59.6	1911-1924
3. North Brush Creek near Saratoga	06622700	37.4	1960-present
4. South Brush Creek near Saratoga	06622900	22.8	1960-1974, 1976-1977, 1979-present
5. Pass Creek near Elk Mountain	06628900	91.5	1957-present
6. Medicine Bow River near Elk Mountain	06630440	28.7	1972-1975
7. EFk Med. Bow River near Elk Mountain	06630480	17.8	1972-1975
8. Rock Creek near Rock River	06632500	64.5	1911-1918, 1939-1965
9. Laramie R. and Pioneer Canal near Woods Landing	06659500	434.0	1912-1916, 1932-1934, 1950-present
10. Little Laramie River near Filmore	06661000	157.0	1902-1903, 1911-1926, 1932-present
11. Non-gaged area on SW side	Estimated using run off values from 06621000		
Sierra Madre Range			
12. Encampment River above Encampment	06624000	207.0	1940-1944
13. Cow Creek near Saratoga	06625500	58.9	1911-1912
14. Spring Creek near Saratoga	06626500	114.0	1911-1912
15. Jack Creek near Saratoga	06627800	109.0	1990-present
16. NFk Little Snake River near Encampment	09251800	9.64	1956-1965
17. Battle Creek near Encampment	09253400	13.0	1956-1963, 1985-1988
18. Savery Creek near Savery	09256000	330.0	1941-1972, 1985-1992
19. Non-gaged area on SE side	Estimated using run off values from 06624000		
20. Non-gaged area on SW side	Covered by over-estimate provided by 09256000		

The cumulative sums of the monthly average were then calculated from the monthly averages in ac-ft. The sums per basin were also normalized to a 90 year mean based on a given gaging station with a long period of record. This was done to eliminate potential high and low biases from data taken during wet and dry years respectively. The gage at Bull Lake Creek near Lenore, Wyoming (USGS ID 06225000) was used for the long period of record (1918-2002) in the Wind River Range. There were no records that ran consistently from 1910's to 2002 in the Sierra Madre or Medicine Bow ranges so two sites were selected to represent the long period of record. They were Little Laramie River near Filmore, Wyoming (USGS ID 06661000) from 1912-1970 and North Brush Creek near Saratoga, Wyoming (USGS ID 06622700) from 1970-2002. The cumulative runoff values were then summed over the entire range to provide an estimate of annual run-off. For many streams in Wyoming, the majority of the runoff and groundwater recharge occurs during the snowmelt runoff period that generally begins in April or May and ends in late July. A summary of the data for the Wind River, Medicine Bow, and Sierra Madre ranges is provided in Table 10.3.

Annual runoff in the Wind River Range (Table 10.3) varies from 3,000 ac-ft at Trout Creek near Fort Washakie to 360,000 ac-ft passing though New Fork River near Cora. Using the numbers presented in Table 10.3, the average annual runoff for the Wind River mountain range is approximately 1,676,477 ac-ft, although that has not been the case over the last 3-6 years. Assuming a 10% augmentation of snowpack and that 80% of this additional snowpack would become runoff, it can be estimated that 8% additional runoff would be generated. This would result in an additional 134,000 ac-ft of water available to the State of Wyoming.

Annual runoff in the Medicine Bow Range varies between 14,000 ac-ft on the East Fork of the Medicine Bow River near Elk Mountain to 132,000 on the Laramie River near Woods Landing. Runoff varies similarly in the Sierra Madre range. Using the numbers provided in Table 10.3, the yearly runoff from the Medicine Bow and Sierra Madre mountain ranges are 565,165 ac-ft and 547,679 respectively. The combined runoff from these ranges total 1,112,845 ac-ft. Assuming an 8% increase in runoff from a conservatively successful snowpack augmentation program, the additional water available would be 89,000 ac-ft.

If seeding the Wind River mountain range yields approximately 134,000 ac-ft of water and the Sierra Madre/Medicine Bow ranges yields 89,000 ac-ft of water, the combined estimate for increased snowpack runoff for the two target areas is approximately 223,000 ac-ft. Keep in mind that this number is based on the mean runoff across the multi-decadal averages provided by the USGS and might be conservative. An increase of 223,000 ac-ft would result in a cost under $8 per ac-ft assuming a program would cost $1,700,000 per year for both mountain ranges. A detailed discussion of the value of an ac-ft in is included in Section 12. Briefly, water values can vary widely based on if the water is used for agriculture or cities. Some transactions with the irrigation districts and the Bureau of Reclamation are around $1 or less. Tribes generally use a number of $10 ac-ft. The Wyoming Water Development Commission estimates 90 percent of the water is used for agriculture which pays $10 to $12 per ac-ft. The other 10 percent of water is used by municipalities/industry at a cost of $75 to $100 (Besson, 2004). All of these estimates suggest the cost of creating the additional water is offset by the amount it is sold for; however these estimates do not include any benefits that might be realized though increased hydro-electric power generation, improved recreation and fisheries, tourism, slowing the melting of glaciers, improved water quality and conditions for certain endangered species, or by meeting downstream water requirements.

Table 10.3 - Summary of annual runoff for the Wind River range and the Medicine Bow/Sierra Madre ranges shown in Figures 10.1 and 10.2. Additional Runoff calculated assuming a 10% increase in snowpack which would produce approximately an 8% increase in runoff.

Area Number (shown in Figure), Stream Gage Location and WY population center the gage is near	Cumulative Annual Runoff (acre-feet)	Basin Total (acre-feet)	Additional Runoff (acre-feet)
Wind River Range			
1. Dinwoody Creek near Burris	101,206		
2. Dry Creek near Burris	32,776		
3. Meadow Creek near Lenore	8,909		
4. Willow Creak near Crowheart	12,260		
5. Bull Lake Creek above Bull Lake	209,885		
6. SFk Little Wind R. above Washakie Res	90,039		
7. NFk Little Wind River near Fort Washakie	94,634		
8. Trout Creek near Fort Washakie	3,391		
9. Middle Popo Agie River near Lander	85,817		
10. North Popo Agie River near Milford	87,963		
11. Little Popo Agie River near Lander	58,911	1,676,477	134,118
12. Green River near Daniel	362,449		
13. New Fork River above New Fork Lakes	25,724		
14. Willow Creak near Cora	4,672		
15. Pine Creek above Fremont Lake	126,347		
16. Pole Creek near Pinedale	98,952		
17. Boulder Creek near Boulder	85,437		
18. East Fork River near Big Sandy	74,541		
19. Silver Creek near Big Sandy	31,955		
20. Big Sandy River at Leckie Ranch	65,241		
21. Little Sandy Creek Near Elkhorn	15,367		
22. Non-gaged area on S side*	0	*Included in value from 06233000*	
Medicine Bow Range			
1. Douglas Creek near Foxpark	58,771		
2. French Creek near French	52,063		
3. North Brush Creek near Saratoga	35,624		
4. South Brush Creek near Saratoga	20,334		
5. Pass Creek near Elk Mountain	31,102	565,165	45,213
6. Medicine Bow River near Elk Mountain	42,126		
7. EFk Med. Bow River near Elk Mountain	14,468		
8. Rock Creek near Rock River	47,194		
9. Laramie R. & Pioneer Canal / Woods Landing	132,601		
10. Little Laramie River near Filmore	72,113		
11. Non-gaged area on SW side*	58,771	*Used value from 06621000*	
Sierra Madre Range			
12. Encampment River above Encampment	186,681		
13. Cow Creek near Saratoga	14,226		
14. Spring Creek near Saratoga	27,994		
15. Jack Creek near Saratoga	16,425	547,679	43,814
16. NFk Little Snake River near Encampment	19,646		
17. Battle Creek near Encampment	21,066		
18. Savery Creek near Savery	74,960		
19. Non-gaged area on SE side*	186,681	*Used value from 06624000*	
20. Non-gaged area on SW side	0	*Included in value from 09256000*	

10.5   Hydrologic Assessment of Snowpack Enhancement Benefits

Current weather modification philosophy suggests that snowpack augmentation should not be considered a "drought busting" technique. It should be considered to be a long-term strategy for water management. However, the benefits during dry years cannot be ignored. The western U.S has recently experienced a drought. In January 2004, the USDA Natural Resources Conservation Service (NRCS) reported that streamflow yield was expected to be approximately 84% of average (USDA-NRCS, 2004). At the same time, the 27 major reservoirs reporting in Wyoming were on average at 50% of their total capacity and 83% of their average storage amount. Specifically, within the two study areas, in the Green River Basin the Fontenelle Reservoir was at 95% and the Flaming Gorge was at 86% of average but the Big Sandy was at 21% of average. In the Wind/Bighorn River Basin, the Boysen Reservoir was at 63% and the Buffalo Bill Reservoir was at 99% of average. In the North Platte Basin, the Seminoe Reservoir was at 41% and the Glendo Reservoir was at 65%, but the Alcova Reservoir was at 101% of average. The readings in June indicated decreased amounts of stored water from the previous year. The percentage with respect to average storage at the end of the snowmelt season was 76%, down from 81% the previous year. An increase in snowpack runoff due to weather modification activities would allow the depleted reservoirs to, at minimum, remain at current levels or hopefully begin to fill. As a long term plan weather modification would allow these reservoirs to remain closer to average and would feed other storage needs.

In 1997, the Wyoming State Legislature directed the WWDC to conduct long range river basin planning. Three water planning basins would be directly impacted by weather modification activities in the Wind River and Sierra Madre/Medicine Bow ranges. These basins include the Wind/Bighorn River Basin, the Green River Basin, and the Platte River Basin. River basin plans have been developed for the first two and is being developed at this time for the latter.

Future municipal and domestic water demands were directly related to population projections in both the Wind/Bighorn and Green River final reports. Under a moderate growth scenario, the Green River plan shows an estimated increase in surface water use from 73% to 82% of the allocation given in the Colorado Compact (including the main stem evaporation charge). Within the Wind/Bighorn Rivers basin, the estimates of total surface water usage increase from 69% to 77% of allowed usage for moderate population growth during a normal year and not including future projects. Including the demands of future projects of the order of 250,000 ac-ft, these projected needs increase to 88% of available flow under a moderate population growth. If it is a dry year, there may be a shortfall. Both basin plans also identify over 40 total facilities for additional of storage of water. As shown previously, a long-term strategy of snowpack augmentation would help with these storage and future use needs. For example, weather modification could help mitigate the impact of a dry year in the Wind/Bighorn River Basin by potentially providing 130,000 to 260,000 ac-ft additional runoff (based on run-off estimates provided in Section 10.4).

There were hundreds of water development projects identified in both river basin plans. Many of the projects that made the short-lists in both basins were tied not only to surface water but also ground water supplies. For example, in the Wind/Bighorn, the plan identified opportunities such as the construction of three Paleozoic wells, development of several storage tanks for transmission and alluvial aquifer augmentation. Over 25 areas were identified as potential ground water areas. Many of these are fed directly by high mountain streams from the Wind River Range. Increased surface flows from weather modification would increase the productivity of these efforts to augment the ground water supply. In the Green River basin, the ground water resources are largely undeveloped. The majority of the current ground water usages

come from Quaternary and Tertiary aquifers for drinking water supplies. Current groundwater use with the Green River Basin is estimated to be 6,200 ac-ft per year. The Green River Basin report suggests that ground water usage is not over-developed at this time due to a potential ground water yield of 50,000 to 100,000 ac-ft per year due to precipitation.

Table 10.4 – Cost Table for other Wyoming Water Supply Projects as Compared to the Proposed Weather Modification Pilot Program (Source: WWDC).

Project	Year	Appropriation	Reservoir Yield (acre-feet)	Construction Cost (per acre-foot yield)	Cost to the State per AF per Year
High Savery Dam **	1988	$4,600,000	9,900	$3,414.14	$158.93*
	1989	$5,000,000			
	1993	$20,400,000			
	2001	$3,800,000			
	Total:	$33,800,000			
Greybull Valley	1994	$3,000,000	12,000	$2,671.45	$124.36*
	1996	$29,057,458			
	Total:	$32,057,458			
Buffalo Municipal Res.	1982-1997 Total:	$13,975,000	1,640	$8,521.34	$396.67*
Split Rock Wellfield	2005-2007 Total:	$11,330,000	5,326	$2,127.30	$227.42***
Weather Modification	2005-2010 Total:	$8,825,000	223,146****	N / A	$7.91
*Costs were annualized over 50 years at 4% interest.					
**Yield is based on an 80% supply for irrigation from the 12,000 acre-feet account, plus 300 AF for municipal use.					
***The wellfield option includes O&M expenses, since this is a substantial cost for a wellfield project, it was annualized over 25 years at 4% interest.					
****Based on a conservative estimate of a 10% increase in snowpack, and a resulting 8% increase in runoff.					

Additionally, there are long term concerns about water quality that could be diminished through the increase in fresh water from snow melt. For example, snow melt water may mitigate the impact of suspended solids as well as human and livestock waste bacteria in the waters of the Wind/Bighorn and tributaries through dilution. Fresh water supplies may decrease the impact of salt and sediment loading of surface flows in the Green River basin. Finally, increased snowmelt would improve surface flow for fisheries found in the cold waters downstream of reservoirs in the North Platte River basin.

11. COST ESTIMATES

Because the cloud seeding programs for the Medicine Bow/Sierra Madre and the Wind River Mountains are similar in form and function, cost estimates are provided for a "single target area", (either), and a "combined target area". In addition, two levels of programs are provided for each.

The comprehensive program would include real-time modeling, statistical evaluation and additional research equipment. In addition, somewhat scaled-back programs that include only the essentials are also presented. These programs would be operational field programs only with one aircraft and ground generators. The basic programs offer less documentation, less ease of evaluation, and less certainty of targeting, but still offer the essentials needed for basic seeding.

The cost estimates are provided in Appendix C and are broken down as follows:

11.1 Single Target Area Program

Basic Program

Comprehensive Program

11.2 Combined Program for the Medicine Bow-Sierra Madre and Wind River Targets

Basic Program

Comprehensive Program

12. PRELIMINARY COST/BENEFIT ANALYSES

To establish the approximate additional water volume that might be attainable through implementation of the cloud seeding program described herein, the natural annual runoff for the maximum period of record available were examined. These figures have been previously presented in Table 10.2.

From the Wind River Mountains, the mean annual runoff is approximately 1,676,477 acre-feet, split between the Green River Basin on the western slope, and the Wind River/Bighorn Basin on the eastern slope. The Medicine Bow Range produces on average an additional 565,165 acre-feet, and the Sierra Madre Range produces an additional 547,679 acre-feet annually, mostly into the North Platte drainage. Thus, the total average annual runoff from the two prospective target areas is 2,789,300 acre-feet.

To begin to assess the impact of seeding, some assumptions are necessary. These are as follows:

1.   *Additional snowfall on the ground will translate to additional soil moisture and/or runoff.* This assumption is reasonable, as a strong correlation between snowpack and runoff is well established. It should be noted that the correlation is likely not to be one-to-one, however. In some circumstances, a fraction of the additional snowpack could be absorbed by the soil and not immediately enter the streamflows. In other circumstances, particularly when the snowpack is near or above average, it is possible that the soil would already be near saturation from the "natural" snowfall, and a greater fraction of the additional snow produced by seeding could contribute to streamflows. Since either scenario is possible and given the large spatial variability of snowpack, perhaps even likely each season, our approach here will be to assume that on average, the relationship will be near one-to-one. In other words, in calculations of the potential benefits of additional snowfall, we will assume that on average, the additional snow thus produced will contribute to runoff in the same proportion as natural snowfall.

2.   *Water storage facilities* in the respective basins appear to be adequate to capture and thus utilize any additional streamflows produced, but should be evaluated further.

3.   *The precise value of water used consumptively within the state is not well established.* General values can be accorded water depending upon its use and location, but precise valuation is not presently possible. General information obtained from the WWDC suggests that ninety percent (90%) of Wyoming's consumptive water use is for agricultural purposes, while the other ten percent (10%) is used by municipalities and industry. The water used by agriculture is generally accorded a value between $10 to $12 per acre-foot, while that used by municipalities and industry is valued between $75 and $100 per acre-foot. Conversation with staff of the Joint Tribal Water Board (Wind River Reservation) indicates a slightly lower range for agricultural and ranching purposes, ranging from $7.50 to $10 per acre-foot. An economic consultant frequently engaged by the WWDC is Mr. Ed Harvey (Ed Harvey, Inc.). In response to our query, Mr. Harvey indicated that water values are increasing. He cited a user in Colorado that is presently paying $5,000 per acre-foot. The City of Fort Collins is presently paying some farmers $400 per acre-foot to increase the available water for municipal use. For the purposes of the valuation of water used consumptively, this study again will take conservative valuations, assuming $11 per acre-foot for agricultural use (the mean of $10-$12), and $87.50 per acre-foot for municipal and industrial use (the mean of $75-$100).

4.   *The value of water used for hydroelectric power generation within Wyoming also varies.* To establish the best estimate possible of the value of this non-consumptive use, the Bureau of Reclamation Office in Mills, Wyoming was contacted. Mr. John Lawson, Area Manager, stated that power generation from Bureau facilities in Wyoming ranged from less than 100 kilowatt hours (kwh) per acre-foot (AF) to over 275 kwh/AF, depending upon the dam and the reservoir level (hydraulic head). It is thus clear that significant additional revenue would be generated by even a modestly effective cloud seeding program, but because of the variability no attempt has been made to quantify this in this study.

5.   *Recreational use and fisheries.* The numerous streams, rivers, lakes and reservoirs surrounding the Wind River and Medicine Bow-Sierra Madre Ranges afford enormous recreational opportunities. In addition to their aesthetic appeal, they offer venues for rafting, boating, and fishing. When the reservoir levels are low, these values are adversely impacted. Boat ramps may become unusable, fish populations suffer, and some streams become characterized by intermittent flows, at best. Wyoming is a very scenic state, and these waters are used not only by in-state residents but also by thousands of out-of-state visitors each year. No assumption of value is made herein, though it is clear that tourism and recreation by both in- and out-of-state visitors is diminished when water supplies are low.

6.   *The State of Wyoming is bound by decree to provide to Nebraska certain flows in the Platte River.* These flows have been depleted in recent years due to drought conditions, which has become a contentious issue between the states. Under Wyoming law, any additional water resulting from cloud seeding activities is treated the same as "natural" water; therefore additional streamflows generated by seeding the Medicine Bow and Sierra Madre Ranges would certainly help mitigate this shortfall. Again, no attempt is made herein to accord a precise value to this potential benefit.

7.   *Threatened and endangered species.*   Low streamflows, lake, and reservoir levels adversely affect all aquatic species, but threatened and endangered species are especially vulnerable. We make no attempt to place a value on such species; this information is provided only to make the reader aware. These species (in Nebraska) include the whooping crane, piping plover, interior least tern, and pallid sturgeon. There may be others.

Expectations for increased snowpack from a well-designed cloud seeding program range from ten to twenty percent, though it is entirely possible this could be exceeded as the program is optimized.

To derive preliminary benefit-to-cost ratios of a seeding program successful at these various levels, the assumptions and facts noted in item 1 through 4 above are applied using the simple economic model below.

Economic Model
In this model, it is assumed that 90% of the additional water generated by cloud seeding is used by agriculture, and is valued at $11 per acre-foot. The other 10% is assumed to be used by industry and municipalities, at a valuation of $87.50 per acre-foot (see again Item 3, above). It is further assumed that 20% of the additional snowpack generated will not be manifested as runoff, but will contribute to groundwater and soil moisture recharge.   Using this model, conservative projections are made for each of three scenarios: a ten percent increase in precipitation (8% increase in runoff), a fifteen percent increase (12% increase in runoff), and a twenty percent increase (16% increase in runoff).

Table 12.1 - Conservative estimates of economic benefit if a ten percent increase in snowpack was achieved through cloud seeding over the Medicine Bow/Sierra Madre Ranges and the Wind River Range. Estimates do not include any valuation of benefits to recreation, fisheries, tourism, or threatened/endangered species.

Runoff Source	Mean Annual Runoff (acre-feet)	Yield if 10% Increase	Less 20% due to recharge	Value
Wind Rivers	1,676,477	167,648	134,118	$2,501,304
Medicine Bow-Sierra Madres	1,112,844	111,284	89,028	$1,660,363
Estimated Totals:	2,789,321	278,932	223,145	$4,161,667
Project Cost:				$1,765,000
Benefit:Cost Ratio				2.36

Table 12.2 - Conservative estimates of economic benefit if a fifteen percent increase in snowpack was achieved through cloud seeding over the Medicine Bow-Sierra Madre Ranges and the Wind River Range. Estimates do not include any valuation of benefits to recreation, fisheries, tourism, or threatened/endangered species.

Runoff Source	Mean Annual Runoff (acre-feet)	Yield if 15% Increase	Less 20% due to recharge	Value
Wind Rivers	1,676,477	251,472	201,177	$3,751,955
Medicine Bow-Sierra Madres	1,112,844	166,927	133,541	$2,490,544
Estimated Totals:	2,789,321	418,398	334,719	$6,242,500
Project Cost:				$1,765,000
Benefit:Cost Ratio				3.54

Table 12.3 - Conservative estimates of economic benefit if a twenty percent increase in snowpack was achieved through cloud seeding over the Medicine Bow-Sierra Madre Ranges and the Wind River Range. Estimates do not include any valuation of benefits to recreation, fisheries, tourism, or threatened/endangered species.

Runoff Source	Mean Annual Runoff (acre-feet)	Yield if 20% Increase	Less 20% due to recharge	Value
Wind Rivers	1,676,477	335,295	268,236	$5,002,607
Medicine Bow-Sierra Madres	1,112,844	222,569	178,055	$3,320,726
Estimated Totals:	2,789,321	557,864	446,291	$8,323,333
Project Cost:				$1,765,000
Benefit:Cost Ratio				4.72

The three scenarios provided here are all very conservative in their outlooks. If the value of the additional water volume to recreation, fisheries, hydropower, tourism, threatened and endangered species, and downstream uses could readily be quantified and included, the projected value would be even greater.

The projected annual cost of $1.765M is significantly greater than that of any other program in the U.S. The primary reason for the cost is that this program, unlike any other anywhere, includes specific plans for *sophisticated numerical modeling*, *physical sampling* (direct evaluation of the physical effects of seeding on the clouds), and *independent evaluation*. All of these are specifically recommended by the National Research Council in its 2003 report to the National Oceanic and Atmospheric Administration (NOAA).

In spite of this, the program is projected to produce a positive outcome in the very first year, even with the most conservative estimates.

As the program becomes well-established and the local nuances of topography, wind flow, and storm patterns better understood, the need for the scientific component will diminish, except of course for continued evaluation. Overall project costs will thus decrease once the optimum program becomes established.

13.   REPORTS AND EXECUTIVE SUMMARIES

Task 13 requires the preparation of reports, and also the writing of an executive summary understandable to lay-persons. This report itself constitutes the first portion of Task 13. An executive summary describing the essential facts and findings of the feasibility study has been prepared for independent publication to complete the second portion of Task 13.

13.1   Reports

This final report address comments and suggestions offered by WWDC staff and the project technical review team comprised of individuals from the National Weather Service, the Natural Resource Conservation Service, the U.S. Geological Survey, the Wyoming State Engineer's Office, and the University of Wyoming. We appreciate their efforts on behalf of the study, and thank them for their constructive comments.

13.2   Revised Executive Summary

The revised executive summary is a much shorter (multi-page) document that summarizes the final report, including projected cost estimates for the various program options. This document is suitable for distribution to those less inclined or without the time needed to read the complete final report. Logically, this audience will include legislators, some water users, and segments of the public as well.

The Executive Summary was revised after it was discovered that the annual streamflow from the Wind River Range, the Sierra Madre Range, and the Medicine Bow Range had been inadvertently but significantly underestimated. In addition, further collaboration with WWDC hydrological staff has fine-tuned the estimates of additional runoff, reflecting some losses to ground water and soil moisture recharge that were not previously accounted for.

Copies of the revised Executive Summary are available from the WWDC web site at wwdc.state.wy.us.

14.   PRESENTATIONS AND HEARINGS

The implementation of a program depends upon the response of the public, stakeholders, special interest groups, and ultimately the legislature.

At study onset, three stakeholder scoping meetings were conducted. In addition, a meeting with the staff of the Riverton National Weather Service Office (31 August 2004) and a meeting with the Joint Tribal Water Board of the Northern Arapaho and Eastern Shoshone Nations (1 September 2004) were also conducted. These meetings were previously summarized in Section 1.

Two additional meetings were conducted in Cheyenne for state and federal resource management agencies.

On Monday, 15 November 2004, WMI and NCAR staff made a short (~25 min) workshop presentation to the WWDC and the Legislative Select Water Committee in Casper, summarizing the findings to that date.

On Tuesday, 16 November 2004, WWDC staff, accompanied by WMI and NCAR staff appeared before a combined meeting of the WWDC and the Legislative Select Water Committee (SWC), also in Casper.

On Wednesday, 17 November 2004, WWDC, WMI, and NCAR staff made a feasibility study presentation to the annual meeting of the Wyoming Association of Conservation Districts, in Cody.

On Wednesday, 1 December 2004, WWDC and NCAR staff made two feasibility study presentations to the annual Woolgrowers and Stockgrowers Convention in Casper.

Advertised public hearings were conducted on Monday, 6 December 2004, in Saratoga (1:00 p.m.) and Lander (6:00 p.m.). Transcriptions of these proceedings are available through the WWDC office.

15.   MONITORING OF STUDY AREAS

This feasibility study is appropriately based heavily upon the climatology of the region, coupled with the most up-to-date knowledge of winter orographic cloud seeding and state-of-the-art numerical modeling.

Despite these efforts, there will no doubt be changes to the operational methodology proposed, some minor, others perhaps not so minor. One very good way to pre-test operational criteria is to monitor the weather within the proposed region to determine how well the criteria perform in real-time, evolving winter weather situations, rather than in the post-hoc analyses used to develop the design.

Task Fifteen of the study is to develop a plan to monitor the study areas through the winter of 2004-2005. Such a plan is set forth here.

15.1   Observation of Wyoming Winter Storms

A number of real-time observational tools are available on the Internet without cost. These include rawinsonde data from weather balloons released from Riverton, upwind of the state from Grand Junction and Boise, and downwind from Denver and Rapid City. These soundings are available twice daily, and will aid in the forecasting of winter storms. Of critical interest in such storms is atmospheric stability, temperatures, and wind directions. Recall that a strong correlation was found between precipitation (over both targets) and westerly winds aloft at 700 mb and 500 mb.

Weather satellites provide real-time imagery around the clock. Visual images are available only during daylight hours, which during the winter are few in number in Wyoming, but infrared and water vapor imagery are available throughout the day and night.

The Wyoming SNOTEL network provides daily (and sometimes more frequent) observations of snowfall in and near both targets.

Wyoming Department of Transportation road reports include driving conditions throughout the state, including the frequently-closed portion of Interstate 80 between Laramie and Rawlins. This study has found that such closures are most often more related to horizontal visibilities reduced by blowing snow than snowfall itself. While snow cannot blow if it does not fall, seeding is proposed in conditions naturally conducive to precipitation. The additional estimated 10-15% produced by seeding is not thought likely to have a perceptible effect. Operational criteria can be compared to actual road closures to assess the frequency with which closures occur naturally during potential seeding conditions. If a seeding program eventually does take place, changes in this frequency can be correlated with actual seeding to determine if visibility problems are exacerbated by seeding. In considering such potential effects, it is important for the reader to be aware that project suspension criteria will be triggered by forecasts of naturally heavy precipitation, and so the naturally efficient storms—the ones known to produce the heaviest snowfall events would likely not be seeded anyway.

Radar imagery from the NWS national network of WSR-88D Doppler weather radars is also available in real-time. However, it must be noted that due to terrain blockages and difficulties in detecting snowfalls with weather radars in general, radar data will not often be a reliable means to determine the locations of snowfall. However, it may help in some circumstances.

The Department of Atmospheric Science at the University of Wyoming in Laramie is assisting with the collection and archival of daily upper air data, which also contributes significantly to this effort.

In spite of a relatively wet start to the 2004-2005 water year, a persistent ridge over the western United States has reduced the frequency of storms during late December 2004 and into early 2005. Nevertheless, some weather systems have still "dug" under the ridge, and have provided additional snowfall in Wyoming during this period. Southern Idaho, on the other hand remains very dry.

15.2   Numerical Modeling

The high-resolution of the WRF model employed for this study might be utilized (through NCAR or a university) to assess where simulated seeding agents released from proposed ground-based sites might be transported and dispersed during an actual seeding event. The same might also be done for airborne releases.

The implementation of this model for the potential target areas has already been funded by this feasibility study, so the cost to do a few simulations in a variety of conditions that meet the seeding criteria would likely be quite be reasonable—and revealing.

15.3   Trace Chemistry

In the original WMI proposal "Task 16" was suggested. That task, had funding allowed, would have provided for the background sampling of silver in the environment in and near the target areas, in both soil and water.

The reasons for this are two-fold. First, silver is easily detected by trace chemistry analysis in concentrations of a few parts per trillion. Silver is also obviously a key ingredient in the silver iodide (AgI) seeding agent complex proposed. If one establishes the natural background levels of silver in the environment before any seeding is ever done, then there can be no debate about the source, i.e., seeding can not be said to have caused what is already present without seeding.

The second reason for silver analysis is that after seeding begins, silver detected within snowfall targeted by the program verifies that the targeting was successful. This latter reason will not be important until operations actually begin, but should be seriously considered, at least during the initial seasons. In addition, should a program continue for several years or more, periodic sampling will provide important environmental data regarding any long-term accumulation of silver.

It is proposed that the environment be tested for silver prior to onset of any operational seeding. Such background measurements will establish a baseline by which any future accumulations can be done. The one-time cost of such work was estimated in 2004 by the Desert Research Institute (DRI) of the University of Nevada, Reno to cost approximately US$25,000. (This quote was provided by Dr. Joe McConnell, whose staff at DRI would do the work independently.)

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Appendix A – Model Physics Options

Listed below are the pertinent physics options used for the Weather Research and Forecast (WRF) modeling simulations. Specific details about these options may be found on the WRF Users website at: http:/www.mmm.ucar.edu/wrf/users/user_main.html.

Physics
cloud microphysics   = Lin, WSM5, WSM6, Thompson
long wave radiation   = rrtm scheme (standard)
short wave radiation   = Dudhia scheme (standard)
radiation time step   = 10 min. between radiation physics calls
surface/clay model   = Monin-Obukhov scheme
land surface model   = Noah land-surface model
boundary layer model   = YSU boundary model
boundary layer time step   = 0 min. between BL physics calls
cumulus parameterization   = none
allow surface fluxes   = yes
allow clouds to affect radiation   = yes
surface input source   = from WRF Standard Input
number of soil ayers   = 4,

Dynamics
dynamics option   = Eulerian mass
time integration scheme   = Runga-Kutta 3rd order,
vertical velocity damping   = off,
turbulence and mixing options   = no turbulence or explicit spatial filters,
upper level damping   = off
number of sound time steps per timestep   = 4
horizontal momentum advection order   = 5
vertical momentum advection order   = 3
horizontal scalar advection order   = 5
vertical momentum advection order   = 3

Appendix B – Addition of Tracer

Below are the coding changes for adding tracer to WRF single moment level 6 and Thompson (module called module_mp_drizzle.F) microphysics package.

A. Registry/Registry.EM
<u>**Added bolded text:**</u>
Moist Scalars
#
The first line ensures that there will be identifiers named moist and
moist_tend even if there are not any moist scalars (so the essentially
dry code will still link properly)
#
state real -   ikjft moist   2   - - -
state real qv   ikjft moist   2   - \
i01rhusdf=(bdy_interp:dt,rqv_b,rqv_bt) "QVAPOR"   "Water vapor mixing ratio"   "kg kg-1"
state real qc   ikjft moist   2   - \
i01rhusdf=(bdy_interp:dt,rqc_b,rqc_bt) "QCLOUD"   "Cloud water mixing ratio"   "kg kg-1"
state real qr   ikjft moist   2   - \
i01rhusdf=(bdy_interp:dt,rqr_b,rqr_bt) "QRAIN"   "Rain water mixing ratio"   "kg kg-1"
state real qi   ikjft moist   2   - \
i01rhusdf=(bdy_interp:dt,rqi_b,rqi_bt) "QICE"   "Ice mixing ratio"   "kg kg-1"
state real qs   ikjft moist   2   - \
i01rhusdf=(bdy_interp:dt,rqs_b,rqs_bt) "QSNOW"   "Snow mixing ratio"   "kg kg-1"
state real qg   ikjft moist   2   - \
i01rhusdf=(bdy_interp:dt,rqg_b,rqg_bt) "QGRAUP"   "Graupel mixing ratio"   "kg kg-1"
# Chem Scalars
< state real -   ikjft chem   2   - - -
**< state real qnt   ikjft chem   2   - **
<   i01rhusdf=(bdy_interp:dt,rqnt_b,rqnt_bt)   "QNTRACER"   "Tracer concentration"   "kg-1"
<u>**Added bolded text:**</u>
state real rqc_b   ikjb misc   -   -   b   "rqc_b"   "MU COUPLED WATER CLOUD MIXING RATIO AT BOUNDARIES"   ""
state real rqc_bt   ikjb misc   -   -   b   "rqc_bt"   "MU COUPLED WATER CLOUD MIXING RATIO TENDENCY AT BOUNDARIES"   ""
state real rqr_b   ikjb misc   -   -   b   "rqr_b"   "MU COUPLED WATER RAIN MIXING RATIO AT BOUNDARIES"   ""
state real rqr_bt   ikjb misc   -   -   b   "rqr_bt"   "MU COUPLED WATER RAIN MIXING RATIO TENDENCY AT BOUNDARIES"   ""
state real rqi_b   ikjb misc   -   -   b   "rqi_b"   "MU COUPLED WATER ICE MIXING RATIO AT BOUNDARIES"   ""
state real rqi_bt   ikjb misc   -   -   b   "rqi_bt"   "MU COUPLED

WATER ICE MIXING RATIO TENDENCY AT BOUNDARIES"   ""
state   real rqs_b   ikjb   misc   -   -   b   "rqs_b"   "MU COUPLED
WATER SNOW MIXING RATIO AT BOUNDARIES"   ""
state   real rqs_bt   ikjb   misc   -   -   b   "rqs_bt"   "MU COUPLED
WATER SNOW MIXING RATIO TENDENCY AT BOUNDARIES"   ""
state   real rqg_b   ikjb   misc   -   -   b   "rqg_b"   "MU COUPLED
WATER GRAUPEL MIXING RATIO AT BOUNDARIES"   ""
state   real rqg_bt   ikjb   misc   -   -   b   "rqg_bt"   "MU COUPLED
WATER GRAUPEL MIXING RATIO TENDENCY AT BOUNDARIES"   ""

**state   real rqnt_b   ikjb   misc   -   -   b   "rqnt_b"   "MU
COUPLED TRACER CONCENTRATION AT BOUNDARIES"   ""**
**state   real rqnt_bt   ikjb   misc   -   -   b   "rqnt_bt"   "MU
COUPLED TRACER CONCENTRATION TENDENCY AT BOUNDARIES"   ""**

Added bolded text:
<   package   wsm6scheme   mp_physics==6   -
moist:qv,qc,qr,qi,qs,qg;**chem:qnt**

B. dyn_em/solve_em.F

Added bolded text:
```
<      CALL microphysics_driver(t_2,moist_2, moist_1, w_2,       &
<                rho, pi_phy, p_phy, RAINNC, RAINNCV,  &
<                z, ht, dz8w, p8w, dtm, dx, dy,      &
<                config_flags, spec_zone,            &
<                num_3d_m, warm_rain,               &
<                XLAND,itimestep,               &
<                F_ICE_PHY,F_RAIN_PHY,F_RIMEF_PHY,    &
<                LOWLYR, chem_2, chem_1, num_3d_c,    &
<                ids, ide, jds, jde, kds, kde,      &
<                ims, ime, jms, jme, kms, kme,       &
<                grid%i_start, min(grid%i_end, ide-1), &
<                grid%j_start, min(grid%j_end, jde-1), &
<                k_start, min(k_end,kde-1), grid%num_tiles )
```

C. phys/module_microphysics_driver.F

Added bolded text:
```
SUBROUTINE microphysics_driver(th_phy, moist_new, moist_old, w,       &
                rho, pi_phy, p_phy, RAINNC, RAINNCV,   &
                z, ht, dz8w, p8w, dt,dx,dy,           &
                config_flags, spec_zone, n_moist,      &
                warm_rain,                    &
                XLAND,itimestep,               &
                F_ICE_PHY,F_RAIN_PHY,F_RIMEF_PHY,     &
                LOWLYR, chem_new, chem_old, n_chem,    &
                ids,ide, jds,jde, kds,kde,            &
                ims,ime, jms,jme, kms,kme,            &
                i_start,i_end,j_start,j_end,kts,kte,num_tiles   )
```

Added bolded text:
```
  REAL, DIMENSION( ims:ime , kms:kme , jms:jme, n_moist ),       &
     INTENT(INOUT) ::                 moist_new
!
```

```
   REAL, DIMENSION( ims:ime , kms:kme , jms:jme, n_chem ),        &
      INTENT(INOUT) ::                        chem_new
!


Added bolded text:
      CASE (WSM6SCHEME)
         CALL wrf_debug ( 100 , 'microphysics_driver: calling wsm6' )
         CALL  wsm6(th_phy,                 &
            moist_new(ims,kms,jms,P_QV),      &
            moist_new(ims,kms,jms,P_QC),      &
            moist_new(ims,kms,jms,P_QR),      &
            moist_new(ims,kms,jms,P_QI),      &
            moist_new(ims,kms,jms,P_QS),      &
            moist_new(ims,kms,jms,P_QG),      &
            chem_new(ims,kms,jms,P_QNT),      &
            w, rho, pi_phy, p_phy, dz8w, RAINNC,&
            RAINNCV,dt,g,cp,cpv,r_d,r_v,SVPT0,  &
            ep_1, ep_2, epsilon, dx, dy,      &
            XLS, XLV, XLF, rhoair0, rhowater,   &
            cliq,cice,psat,               &
            ids,ide, jds,jde, kds,kde,        &
            ims,ime, jms,jme, kms,kme,        &
            its,ite, jts,jte, kts,kte         )
```

D. phys/module_mp_wsm6.F

Added bolded text:

In the variable declaration section at top of module…

```
  REAL, PARAMETER, PRIVATE :: t40c = 233.16
  REAL, PARAMETER, PRIVATE :: eacrc = 1.0
  REAL, PARAMETER, PRIVATE :: dens  =  100.0
  REAL, PARAMETER, PRIVATE :: qs0   = 6.e-4   ! pgaut
  REAL, PARAMETER, PRIVATE :: dom3dx = 1000.0
  INTEGER, PARAMETER, PRIVATE :: iloc = 72
  INTEGER, PARAMETER, PRIVATE :: jloc = 72
  INTEGER, PARAMETER, PRIVATE :: kloc = 1
```

Added bolded text:

```
SUBROUTINE wsm6(th, q, qc, qr, qi, qs, qg, qnt,         &
            w, den, pii, p, delz, rain, rainncv,      &
            delt,g, cpd, cpv, rd, rv, t0c,         &
            ep1, ep2, qmin, dx, dy,            &
            XLS, XLV0, XLF0, den0, denr,          &
            cliq,cice,psat,                 &
            ids,ide, jds,jde, kds,kde,          &
            ims,ime, jms,jme, kms,kme,           &
            its,ite, jts,jte, kts,kte             )

  REAL, DIMENSION( ims:ime , kms:kme , jms:jme ),          &
      INTENT(INOUT) ::                    &
```

```
.
.
.
                                        qs, &
                                        qg, &
                                        qnt

REAL, INTENT(IN   ) ::                  delt, &
.
.
.
                                        qmin, &
                                        dx, &
                                        dy, &
                                        XLS, &
.
.
.

! LOCAL VAR
  REAL, DIMENSION( its:ite , kts:kte ) ::   t, qntz
  REAL, DIMENSION( its:ite , kts:kte, 2 ) ::  qci
  REAL, DIMENSION( its:ite , kts:kte, 3 ) ::  qrs
  INTEGER ::          i,j,k,rtile
```

Added bolded text:

```
!---- Start Put 3D variables into a belt along a single lat line ----
    DO j=jts,jte
      DO k=kts,kte
      DO i=its,ite
        t(i,k)=th(i,k,j)*pii(i,k,j)
        qci(i,k,1) = qc(i,k,j)
        qci(i,k,2) = qi(i,k,j)
        qrs(i,k,1) = qr(i,k,j)
        qrs(i,k,2) = qs(i,k,j)
        qrs(i,k,3) = qg(i,k,j)
        qntz(i,k) = qnt(i,k,j)
      if (rtile .eq. 1) print *, i, k, j, 'qnt(i,k,j) = ', qnt(i,k,j)
      ENDDO
      ENDDO
!-----------------------------------------------------------------
      CALL wsm62D(t, q(ims,kms,j), qci, qrs, qntz,         &
            w(ims,kms,j), den(ims,kms,j),            &
            p(ims,kms,j), delz(ims,kms,j), rain(ims,j),   &
            rainncv(ims,j),delt,g, cpd, cpv, rd, rv, t0c, &
            ep1, ep2, qmin,                    &
            XLS, XLV0, XLF0, den0, denr,            &
            cliq,cice,psat,                    &
            j, dx, dy,                      &
            ids,ide, jds,jde, kds,kde,            &
```

```
                  ims,ime, jms,jme, kms,kme,              &
                  its,ite, jts,jte, kts,kte               )
        DO K=kts,kte
        DO I=its,ite
          th(i,k,j)=t(i,k)/pii(i,k,j)
          qc(i,k,j) = qci(i,k,1)
          qi(i,k,j) = qci(i,k,2)
          qr(i,k,j) = qrs(i,k,1)
          qs(i,k,j) = qrs(i,k,2)
          qg(i,k,j) = qrs(i,k,3)
          qnt(i,k,j) = qntz(i,k)
        ENDDO
        ENDDO
      ENDDO
    END SUBROUTINE wsm6
!======================================================================
!
    SUBROUTINE wsm62D(t, q, qci, qrs, qntz, w, den, p, delz, rain,   &
                  rainncv,delt,g, cpd, cpv, rd, rv, t0c,        &
                  ep1, ep2, qmin,                   &
                  XLS, XLV0, XLF0, den0, denr,           &
                  cliq,cice,psat,                   &
                  lat, dx, dy,                   &
                  ids,ide, jds,jde, kds,kde,            &
                  ims,ime, jms,jme, kms,kme,            &
                  its,ite, jts,jte, kts,kte             )
!------------------------------------------------------------


Added bolded text:
REAL, DIMENSION( its:ite , kts:kte ),              &
     INTENT(INOUT) ::                   &
                               t,qntz

REAL, INTENT(IN   ) ::                   delt, &
                                  g, &
                                cpd, &
                                cpv, &
                                t0c, &
                                den0, &
                                 rd, &
                                 rv, &
                                ep1, &
                                ep2, &
                                qmin, &
                                 XLS, &
                                XLV0, &
                                XLF0, &
                                cliq, &
                                cice, &
                                psat, &
```

```
                              denr, &
                              dx,dy
```

Added bolded text:
```
!-------------------------------------------------------------
!    paddint 0 for negative values generated by dynamics
!
    do k = kts, kte
      do i = its, ite
        qci(i,k,1) = max(qci(i,k,1),0.0)
        qrs(i,k,1) = max(qrs(i,k,1),0.0)
        qci(i,k,2) = max(qci(i,k,2),0.0)
        qrs(i,k,2) = max(qrs(i,k,2),0.0)
        qrs(i,k,3) = max(qrs(i,k,3),0.0)
        if (qntz(i,k).le.0.0) qntz(i,k)  = -1.*qntz(i,k)
      enddo
    enddo
!
!-------------------------------------------------------------
```

Added
! adding tracer

! Passive tracer material added in one grid block
! Assume generator releases 2.4e+16 nuclei/hour as in Arizona Dept of
! Water Resources 1989 report
! Units #/kg
! I is the number of grid points from along the x-axis (longitude) and j
! is the number of grid points along the y-axis (latitude)
! The tracer is only released when the horizontal resolution is 1 km
! (inner domain; dx) and the timestep is greater than a certain value
! (to control start time)

```
    if (lat.eq.jloc.and.dx.eq.dom3dx) then
      do i=its, ite
        if (i.eq.iloc) then
          qntzs = 2.4e+16/((3600.0*dx*dy*delz(i,kloc))*den(i,kloc))
          qntz(i,kloc) = qntz(i,kloc)+(qntzs*dtcld)
        endif
      enddo
      print *, 'out tracer loop', i, qntz(iloc,kloc)
    endif
```

E. phys/module_mp_drizzle.F

To SUBROUTINE drizzle(…   , add
qnt,
P_QNT,
dx_in, dy_in,

To INTEGER, INTENT (IN   ) :: , add
P_QNT,

```
To REAL, INTENT (INOUT) :: , add
qnt,

To REAL, INTENT(IN    ) :: , add
dx_in, dy_in,

To REAL, DIMENSION (kts:kte) :: , add
qntz

To REAL :: , add
qnt_max,        (only version 2)
dx, dy,

qnt_max = 0.   (only version 2)

dx = dx_in,
dy = dy_in,

Write data from 3-D to 1-D:  add
IF (P_QNT .ge. P_FIRST_SCALAR) THEN
        DO k=kts, kte
                qntz(k) = qnt(I,k,j)
        ENDDO
ELSE
        DO k=kts,kte
                qntz(k)=0.
        ENDDO
ENDIF

CALL exmoish(… , add
itimestep,
qntz,
dx, dy

qnt_max = amax1(qnt_max,qntz(k))   (only version 2)

Update data from 1-D back to 3-D:
IF (P_QNT .ge. P_FIRST_SCALAR) THEN
        DO k=kts, kte
                qnt(I,k,j) = qntz(k)
        ENDDO
ENDIF

SUBROUTINE exmoish(… , add
itimestep,
qntz,
dx, dy,

REAL, DIMENSION (kts:kte), INTENT (INOUT) :: , add
```

```
qntz

REAL DIMENSION (kts:kte) :: , add
qntzten

REAL, INTENT (IN    ) :: , add
dx, dy,

INTEGER, INTENT (IN    ) :: , add
itimestep,

qntzten(k) = 0.

qntz(k) = AMAX1(0.,qntz(k))

After GRAUPEL TENDENCY, add

! TRACER TENDENCY
! Passive tracer material added in one grid block
! Asume generator releases 2.4e+16 nuclei/hour as in Arizona Dept of
! Water Resources 1989 report
! Units #/kg
! I is the number of grid points from along the x-axis (longitude) and j
!  is the number of grid points along the y-axis (latitude)
! The tracer is only released when the horizontal resolution is 1 km
!  (inner domain; dx) and the timestep is greater than a certain value
!  (to control start time)

IF (i.EQ.72, and.j.EQ.72.and.k.EQ.kts.and.dx.EQ.1000.and.
& itimestep.GE.1) THEN
qntzTEN(k)=2.4e+16/(3600.0*dx*dy*dzw(k))*rhoz(k)
ELSE
        qntzTEN(k)=0.
ENDIF

qntz(k)=qntz(k)+qntzten(k)*dt
```

Appendix C – Cost Estimates

WYOMING LEVEL II FEASIBILITY STUDY PROGRAM BUDGET NOVEMBER 15 THROUGH MARCH 31 FIVE-YEAR PROGRAM		
SINGLE SITE BASIC PROGRAM		
	One Time Budget	Annual Budget
ENVIRONMENTAL, PERMITS AND EASEMENTS		
2 Environmental Assessments (if necessary)	$100,000	
Permits	$4,000	
Landowner Easements	$2,000	
SEEDING AND RESEARCH EQUIPMENT		
1 Propjet Research Aircraft with Cloud Seeding		$375,360
Complete cloud physics research package		
20 flight hours per month total		
Configured for cloud base and cloud top seeding		
Qty. 1,000 20-gram Ejectable Flares		
Qty. 750 150-gram Burn-in-Place Flares		
All fuel, oil, maintenance, parts and insurance		
12 Remote-Control Ground-Based Ice Nuclei Generators		$174,874
2 Meteorological Stations		
100 gallons Seeding Agent per Generator for the season		
PERSONNEL – FIELD PROGRAM		$384,836
1 Program Manager Meteorologist		
1 Propjet Captain		
1 First Officer		
2 Data System/Ground Generator Technicians		
TIME FRAME FIELD PROGRAM		
November 15 through March 31		
TOTALS	**$106,000**	**$935,070**
FOR EACH YEAR AFTER YEAR ONE, INCLUDE A 3% COST INCREASE		

WYOMING LEVEL II FEASIBILITY STUDY PROGRAM BUDGET NOVEMBER 15 THROUGH MARCH 31 FIVE-YEAR PROGRAM SINGLE SITE COMPREHENSIVE PROGRAM	One Time Budget	Annual Budget
ENVIRONMENTAL, PERMITS AND EASEMENTS		
2 Environmental Assessments (if necessary)	$100,000	
Permits	$4,000	
Landowner Easements	$2,000	
DATA MODELING SYSTEM		
Computer Bank for Real-Time Data Modeling (annual lease)		$50,600
Annual Model Implementation and Maintenance		$50,000
STATISTICAL EVALUATION		$100,000
MODELING – CLOUD AND PRECIPITATION FORMATION		$60,000
NCAR SOFTWARE (TITAN/CIDD/REC) FOR RADAR UPGRADE (annual lease)		$38,000
RADIOMETER (annual lease)		$50,600
VAISALA WEATHER BALLOON SYSTEM WITH DAILY LAUNCH (includes annual lease and daily launch costs)		$58,050
SEEDING AND RESEARCH EQUIPMENT		
1 Propjet Research Aircraft with Cloud Seeding		$375,360
Complete Cloud Physics Research Package		
20 Flight Hours per month total		
Configured for Cloud Base and Cloud Top Seeding		
Qty. 1,000 20-gram Ejectable Flares		
Qty. 750 150-gram Burn-in-Place Flares		
All Fuel, oil, maintenance, parts and insurance		
12 Remote-Control Ground-Based Ice Nuclei Generators		$174,874
2 Meteorological Stations		
100 gallons Seeding Agent per Generator for the season		
PERSONNEL – FIELD PROGRAM		$384,836
1 Program Manager Meteorologist		
1 Propjet Captain		
1 First Officer		
2 Data System/Ground Generator Technicians		
TIME FRAME FIELD PROGRAM		
November 15 through March 31		
TOTALS	**$106,000**	**$1,342,320**
FOR EACH YEAR AFTER YEAR ONE, INCLUDE A 3% COST INCREASE		

WYOMING LEVEL II FEASIBILITY STUDY PROGRAM BUDGET NOVEMBER 15 THROUGH MARCH 31 **FIVE-YEAR PROGRAM** **COMBINED BASIC PROGRAM**	One Time Budget	Annual Budget
ENVIRONMENTAL, PERMITS AND EASEMENTS		
2 Environmental Assessments (if necessary)	$100,000	
Permits	$4,000	
Landowner Easements	$2,000	
SEEDING AND RESEARCH EQUIPMENT		
1 Propjet Research Aircraft with Cloud Seeding		$488,704
Complete cloud physics research package		
20 flight hours per month total		
Configured for cloud base and cloud top seeding		
Qty. 2,000 20-gram Ejectable Flares		
Qty. 1,500 150-gram Burn-in-Place Flares		
All fuel, oil, maintenance, parts and insurance		
24 Remote-Control Ground-Based Ice Nuclei Generators		$277,619
4 Meteorological Stations		
100 gallons Seeding Agent per Generator for the season		
PERSONNEL – FIELD PROGRAM		$444,452
1 Program Manager Meteorologist		
1 Propjet Captain		
1 First Officer		
1 Assistant Meteorologist		
2 Data System/Ground Generator Technicians		
TIME FRAME FIELD PROGRAM		
November 15 through March 31		
TOTALS	**$106,000**	**$1,210,775**
FOR EACH YEAR AFTER YEAR ONE, INCLUDE A 3% COST INCREASE		

WYOMING LEVEL II FEASIBILITY STUDY PROGRAM BUDGET NOVEMBER 15 THROUGH MARCH 31 **FIVE-YEAR PROGRAM** **COMBINED COMPREHENSIVE PROGRAM**	One Time Budget	Annual Budget
ENVIRONMENTAL, PERMITS AND EASEMENTS		
2 Environmental Assessments (if necessary)	$100,000	
Permits	$4,000	
Landowner Easements	$2,000	
MODELING SYSTEM		
Computer Bank for Real-Time Data Modeling (annual lease)		$50,600
Annual Model Implementation and Maintenance		$50,000
STATISTICAL EVALUATION		$100,000
MODELING – CLOUD AND PRECIPITATION FORMATION		$60,000
NCAR SOFTWARE (TITAN/CIDD/REC) FOR RADAR UPGRADE (annual lease)		$38,000
RADIOMETER (annual lease)		$50,600
VAISALA WEATHER BALLOON SYSTEM WITH DAILY LAUNCH (includes annual lease and daily launch costs)		$58,050
SEEDING AND RESEARCH EQUIPMENT		
1 Propjet Research Aircraft with Cloud Seeding		$488,704
Complete Cloud Physics Research Package		
20 Flight Hours per month total		
Configured for Cloud Base and Cloud Top Seeding		
Qty. 3,000 20-gram Ejectable Flares		
Qty. 1,500 150-gram Burn-in-Place Flares		
All Fuel, oil, maintenance, parts and insurance		
24 Remote-Control Ground-Based Ice Nuclei Generators		$277,619
4 Meteorological Stations		
100 gallons Seeding Agent per Generator for the season		
PERSONNEL – FIELD PROGRAM		$444,452
1 Program Manager Meteorologist		
1 Propjet Captain		
1 First Officer		
1 Assistant Meteorologist		
2 Data System/Ground Generator Technicians		
TIME FRAME FIELD PROGRAM		
November 15 through March 31		
TOTALS	**$106,000**	**$1,618,025**
FOR EACH YEAR AFTER YEAR ONE, INCLUDE A 3% COST INCREASE		

Appendix D – Glossary of Terms

Definitions are those found within the Glossary of Meteorology, where applicable. Italicized print in this section indicates an alternative glossary entry that the reader may also wish to review.

acoustic ice nucleus counter – Sometimes called an "NCAR counter", this instrument can be operated either on the ground of on an airplane. It is used to sample the atmosphere and "count" *ice nuclei*. The acoustic ice nucleus counter will count both natural and artificial ice nuclei, but cannot distinguish between them.

adiabatic – A process in which a thermodynamic "system" does not interact with its surroundings by virtue of a temperature difference between them.

advection – The process of transport of an atmospheric property (e.g. temperature) by the horizontal or vertical motions (winds) of the atmosphere. Vertical transport due to buoyancy is a specialized form of advection known as *convection.*

AF – acre-foot or acre-feet.

AgI – see *silver iodide.*

albedo – The ratio of reflected light to incident light. Fresh snow has a large albedo. Evergreen forests have a small albedo.

AMS – American Meteorological Society, 45 Beacon Street, Boston, MA 02108-3693.

anemometer – The general name for instruments designed to measure the wind.

BLM – Bureau of Land Management, U.S. Department of the Interior.

BuRec – United States Bureau of Reclamation, Department of the Interior.

calcium chloride – ($CaCl_2$) A simple salt often used as a primary ingredient in hygroscopic cloud seeding pyrotechnics.

CCN – Cloud condensation nuclei. The tiny particles, either liquid or solid, upon which condensation of water vapor first begins in the atmosphere, they are necessary for the formation of cloud droplets.

cloud condensation nuclei – See *CCN.*

CD-ROM – Compact disk, read-only memory. The common compact diskette (CD) used for data archival and musical recordings.

cell – A convective element (cloud) which in its life cycle, develops, matures, and dissipates, usually in about 30 min.

cloud droplet – A particle of liquid water from a few microns to tens of microns in diameter formed by condensation of atmospheric water vapor and suspended in the atmosphere with other droplets for form a cloud. These liquid water droplets are too small to precipitate.

cloud droplet spectrum – The collective numbers of cloud droplets of each size measured in a given cloud sample.

cloud model – Physical description of cloud processes programmed into a computer to simulate cloud development and evolution. Very useful in understanding the relative importance of the many factors that influence cloud development, and the only way in which *exactly the same cloud* can be both seeded and unseeded (see also *targeting model*).

CLW – Cloud liquid water. CLW differs from *SLW* in that CLW includes both supercooled and non-supercooled cloud water.

coalescence – In cloud physics, the merging of two water drops into a single larger drop. This occurs through the collision or two drops, which then unite.

conceptual mode – A theoretical model of precipitation development, based upon current knowledge and scientific concepts. See also *cloud model*.

convection – Vertical transport of an atmospheric property (e.g. temperature) by the vertical motions (winds) in the atmosphere driven by buoyancy.

CYS – Official National Weather Service identifier for Cheyenne, Wyoming.

DAS – Department of Atmospheric Science, University of Wyoming, Laramie.

differential reflectivity (Z$_{DR}$) – The ratio of the radar reflectivity measured by two signals that differ in one attribute, for example, polarization or wavelength. The dual-polarization conversions planned for the National Weather Service radars would effectively make the sets capable of differentiating between water cloud and ice cloud.

dew point – The temperature at which air, if cooled, will condense.

direct targeting – The placement of seeding agents directly into the targeted cloud by release *at* the targeted cloud.

droplet spectrum – The numbers and sizes of the droplets within the cloud volume of interest.

EA – Environmental Assessment. A preliminary assessment of potential environmental impact of a planned activity. An EA will result in either the conduct of an *EIS*, or a *FONSI*.

EIS – Environmental Impact Statement. A detailed environmental study pertaining to planned activities, conducted after an *EA*, in accordance with *NEPA*.

EMO – Elk Mountain Observatory operated by the University of Wyoming Department of Atmospheric Sciences.

EVID – Eden Valley Irrigation District headquartered in Farson, Wyoming.

FAA – Federal Aviation Agency, U.S. Department of Transportation.

FBO – Fixed-base operator. Airport-based business which provides fuel, maintenance, and often other aviation-related services.

FONSI – Finding Of No Significant Impact. One of two possible results from an *EA*. See also, *EIS*.

FSSP – Forward-Scattering Spectrometer Probe. A laser-driven sensor used to count and measure cloud droplets.

glaciogenic – Causing the formation of ice.

glaciogenic seeding – Treatment of clouds with materials intended to increase and/or initiate the formation of ice crystals.

GPS – Global Positioning System. A global, satellite-based navigation positioning system which provides consistently accurate positions.

graupel – White, opaque, approximately round (sometimes conical) ice particles having a snow-like structure, and about 2-5 mm in diameter. Also known as snow pellets, they form in convective clouds when supercooled water droplets freeze to an ice particle upon impact.

grid spacing – The distance between two points in a numerical (computer) model grid. Calculations derived from atmospheric theory and pertinent to the solution of the model are performed at each grid point by the computer.

ground generator – An ice nucleus generator operated on the surface.

hail – Precipitation in the form of balls or irregular lumps of ice, always produced by convective clouds, nearly always by cumulonimbus. An individual unit of hail is called a hailstone. By convention, hail has a diameter of 5 mm or more.

hydrometeor – Any product of condensation or deposition, or condensation and freezing, in the atmosphere. This includes cloud water or ice of any size, either suspended in the air or precipitating.

hygroscopic – Pertaining to a marked ability to accelerate the condensation of water vapor; having the property of attracting water, or having the effect of encouraging the formation of larger droplets.

hygroscopic seeding – Treatment of clouds with hygroscopic materials which encourage the formation of larger droplets, changing the cloud droplet spectrum in such a way as to enhance development of precipitation through coalescence.

IFN – Ice forming nucleus (see *ice nucleus*).

ice nucleus – Any particle that serves as a nucleus for the formation of ice crystals in the atmosphere.

IFR – Instrument Flight Rules. The FAA regulations pertaining to flight at altitudes of 18,000 feet above mean sea level or higher over U.S. airspace, or in any meteorological conditions necessitating the use of aircraft instrumentation for safe navigation.

IN – See *ice nucleus*.

***in situ* measurement** – Measurements made within the portion of the atmosphere or cloud of interest. Compare *remote sensing*.

KDP or Specific Differential Phase – dual-polarization radar can measure the phase velocity difference between the horizontal and vertical pulses as the waves propagate through precipitation (ΦDP). The range derivative of ΦDP is KDP (or K_{DP}). Some advantages of KDP are that it is closely related to rainwater content and unaffected by spherical ice in the radar pulse volume, and it is relatively insensitive to attenuation, partial beam blocking, and absolute radar calibration.

latent heat – The heat released or absorbed per unit mass by a system in a reversible, isobaric-isothermal change of phase. More simply, the heat released when water vapor condenses (latent heat of condensation), or when liquid water drops freeze (latent heat of fusion). In the case of water droplets freezing upon contact with hail, the latent heat elevates the surface temperature of the growing hailstone.

mb – Millbar. A unit of pressure equal to one hecto-Pascal (hPa). Standard sea-level pressure is 1013.25 mb.

mesoscale – Weather features on the order of 1 to 100 km in horizontal dimensions.

MIC – Meteorologist-In-Charge. The manager of each National Weather Service office is the MIC.

microphysical – Very small scale features of a system, in this case, a cloud. These features include the sizes, shapes, and number of raindrops, cloud drops, ice, snow, graupel, and hail.

MSL – Mean Sea Level.

NCAR – National Center for Atmospheric Research, Boulder, Colorado.

NEPA – National Environmental Policy Act. Federal environmental study rules and regulations employed whenever any action is planned that may affect federal lands.

nesting – A process where one grid cell for a numerical model is split into the designated number in the nesting ratio. For example, if the ratio is 3-to-1, the original cell would be split into three, at computations would be performed at all three points. This is a way to increase the resolution of a model over a specific region of interest.

NOAA – National Oceanic and Atmospheric Administration, U.S. Department of Commerce. The parent agency of the National Weather Service (NWS).

nowcasting – Very short-term forecasting, from the present to about 30 minutes.

NRC – National Research Council, Washington, D.C.

NRCS – Natural Resources Conservation Service.

NRRI – Natural Resources Research Institute, University of Wyoming, Laramie.

nucleation – The initial formation of a cloud droplet or ice crystal.

NWS – National Weather Service, a division of *NOAA*.

orographic cloud – A cloud formed by terrain induced lifting of moist air, for example, air forced to rise to pass over a mountain.

orography – Topography, terrain, vertical relief.

polarimetric – A weather radar having dual polarization capability. See also *differential reflectivity*.

PSU-NCAR-MM5 – Pennsylvania State University – *NCAR* – Mesoscale Meteorological Model Version 5. A widely-used numerical model first developed at PSU.

pyrotechnic – Special flare designed to produce *glaciogenic* or *hygroscopic* nuclei.

MST – Mountain Standard Time. Seven hours slower than GMT, CUT, and UTC. For example, 3:00 p.m. MDT equals 10 p.m. (22:00) UTC.

radiation – The process by which electromagnetic radiation is propagated through free space. The propagation takes place at the speed of light (3.00×10^8 meters per second).

radiometer – A device which passively senses microwave radiation at varying wavelengths as it passes through the atmosphere from space. Certain atmospheric constituents, for example liquid water and water vapor, attenuate the incoming radiation. Thus, these quantities can be measured by radiometers.

radiosonde (**or rawinsonde**) – An instrument package that senses and transmits weather information such as pressure, temperature, and humidity. Radiosondes are carried aloft by weather balloons twice daily from numerous sites all over the world, and can also be employed by projects to bolster local forecasting efforts.

raindrop – A drop of water of diameter greater than 0.5 mm falling through the atmosphere. In careful usage, falling drops with diameters lying in the interval 0.2 to 0.5 mm are called drizzle drops rather than raindrops. This is frequently overlooked.

RAL (formerly RAP) – The Research Application Laboratory (Research Applications Program) at *NCAR*.

RAMS – Regional Atmospheric Modeling System. A widely-used numerical model developed by Colorado State University scientists.

reflectivity (or equivalent radar reflectivity factor, Z_e) – The energy, first transmitted by a weather radar, reflected back toward the radar. In general, the more "dense" the reflecting cloud mass, the greater will be the reflectivity. Ice reflects about one-fifth the energy reflected by water, however, so reflectivities from snow are accordingly less.

remote sensing – The remote measurement of properties of interest, as with radar and satellite. Compare *in situ measurement*.

response time – The time that elapses from identification of a seeding opportunity until the release of seeding agent actually begins.

RIW – Official NWS designator for the Riverton, Wyoming, office.

Runga-Kutta – A numerical analysis technique for solving ordinary differential equations (used in numerical modeling).

seeding agents – Agents dispensed by any means in or near a cloud volume which are intended to modify (seed) the cloud characteristics.

SERCD – Saratoga Encampment Rawlins Conservation District.

silver iodide – AgI, a common glaciogenic seeding agent.

SLW – Supercooled liquid water, see *supercooled water*.

SNOTEL – Snow measurement and telemetry site operated by the *NRCS*.

SOO – The Science and Operations Officer of a NWS office.

SPP – Upgraded version of *FSSP* cloud physics probe.

specific differential phase – see *KDP*.

supercooled liquid water – Water, still in liquid state, at temperatures less than $0^{\circ}C$ ($32^{\circ}F$). Under ideal conditions in the free atmosphere, water may exist in a supercooled state to temperatures as cold as $-40^{\circ}C$ ($-40^{\circ}F$).

submicron – Aerosol particles of dimensions less than one micron.

SWC – Select Water Committee of the Wyoming State Legislature.

SWE – Snow water equivalent.

synoptic scale – Weather features of horizontal dimensions greater than 100 km.

target area – The area for which cloud seeding operations are targeted, usually near a *control area* similar in character and climatology. The behavior of treated storms over the target area is compared to untreated storms over the control area, to assess differences and thus measure project effectiveness. See also, *control area*, *seeding area*, and *seeded area*.

targeting model – Computer modeling in which terrain and winds are used to project when and where cloud seeding upwind of a target area should be conducted.

terminal velocity – The particular falling speed, for any given object moving through a fluid of specified physical properties, at which the drag forces and buoyant forces exerted by the fluid on the object just equal the gravitational force acting on the object. For hydrometeors, the greatest fall speed relative to the surrounding air that a hydrometeor will attain, as determined by the mass of the particle and frictional drag of the air through which it is falling.

thermal – A relatively small-scale, rising current of air produced when the atmosphere is heated enough locally by the earth's surface to produce absolute instability in the lowest layers.

tracer – An inert (non-reactionary) substance or aerosol that is dispersed into the atmosphere, commonly used to reveal wind flow patterns. In numerical modeling, there are no other calculations performed for tracers other than horizontal and vertical advection.

USDA – United States Department of Agriculture, parent organization of the *Forest Service*.

USFS – United States Forest Service, a division of the *USDA*.

UTC – Universal Time Coordinates. See also *GMT*, *CUT*.   Seven hours ahead of Mountain Standard Time; for example, 10:00 p.m. UTC (22:00) equals 3:00 p.m. (17:00) MST.

UW – University of Wyoming, Laramie.

VFR – Visual flight rules established by the *FAA* that state the requirements for flight in "visual" conditions.

VIL – Vertically integrated liquid. A radar estimate of the cloud liquid water, from the lowest angle sampled through cloud top. Used as an indicator of the presence of hail.

VOR – Direction, from zero to 360 degrees, from a *VORTAC*. Zero (and 360°) is north, 90° is east, 180° is south, and 270° is west.

VORTAC – Aviation navigational aid, which uses radio to provide a direction (radial) and distance from the location of the VORTAC.

WCM – The Warning Coordination Meteorologist of a NWS office.

wind profiler – The NOAA Profiler Network (NPN), consists of 35 unmanned Doppler radar sites located in 18 central US states and Alaska, provides hourly vertical wind profile data. The data produced by this network are distributed to the National Weather Service (NWS), environmental research groups, and Universities.   The NPN has been operating continuously since 1992 and celebrated its 10th Anniversary in 2002. There is a wind profiler located near Medicine Bow, Wyoming that provides useful real-time vertical wind data.

wing-tip generator – Ice nucleus generators mounted at the tips of aircraft wings, or sometimes below the wings (usually near the ends).

WMA – Weather Modification Association, P.O. Box 26926, Fresno, CA 93729-6926.

WMI – Weather Modification, Inc., Fargo, North Dakota.

WRF – The Weather Research and Forecasting Model employed by RAL to study wind flow, transport and dispersion of seeding agents, and precipitation development within (and beyond) the areas of interest.

WWDC – Wyoming Water Development Commission, Cheyenne, Wyoming.

WYDOT – Wyoming Department of Transportation, Cheyenne, WY.