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

Financial Assistance Agreement No. 03-FC-81-0925
Second Quarterly Technical Progress Report
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Table of Project Team:

Name	Organization	Phone	E-mail
Joe Busto	CWCB	(303) 866-4807	Joe.busto@dwr.state.co.us
Curt Hartzell	Consultant	(320) 222-8780	curtjoan@en-tel.net
Ross Williams	Consultant	(719) 473-7333	rawscoe@adelphia.net
Steve Schmitzer	Denver Water	(303) 628-6525	Steve.Schmitzer@denverwater.org
Becky Dechant	Denver Water	(303) 628-6538	Becky.Dechant@denverwater.org
Greg Bryant	Denver Water	(303) 628-6543	Greg.Bryant@denverwater.org
Larry Hjermstad	Western Weather	(970) 247-8813	westernweather@sprynet.com
William Cotton	Colorado State U.	(970) 491-8593	cotton@atmos.colostate.edu
Brenda Thompson	Colorado State U.	(970) 491-8593	brenda@atmos.colostate.edu
Ray McAnelly	Colorado State U.	(970) 491-8341	raymc@atmos.colostate.edu
Gustavo Carrió	Colorado State U.	(970) 491-8508	carrio@atmos.colostate.edu
Paul Mielke	Colorado State U.	(970) 484-3374	rrmielke@aol.com

Overview of Project Status

The Financial Assistance Agreement between the U.S. Bureau of Reclamation (Reclamation) and the Colorado Water Conservation Board (CWCB) required a midterm project review meeting. This meeting was hosted by Colorado State University (CSU), Department of Atmospheric Science, on February 19, 2004. The summary for this meeting will be posted on the CSU website at http://rams.atmos.colostate.edu/clseeding/

There was considerable progress made during the second quarter of the Colorado WDMP research project. Operational cloud seeding activities for the Denver Water Program were concluded, and a final seeding activities log was provided to Denver Water and CSU. A list of 30 operational days was selected for use in project studies; a meteorological wind regime was assigned to each day. Work was done on the development of GIS seeding dispersion graphics. The Seeding Test Case for February 4, 2003 was completed. The MRBP analysis code was updated and documented. The CSU PC cluster was used for realtime runs and for control and seeding runs. And the gathering of data needed for the project studies continued.

The Statement of Work in the CWCB-CSU Contract listed 16 deliverables related to the six tasks; nine of these deliverables had been completed. These nine deliverables comprise about 64.5 % of the CWCB-CSU Contract. The tasks for the three deliverables and other work completed during the second quarter will be summarized in following subsections of this technical progress report.

Denver Water's and the Central Rockies Cloud Seeding Programs:

The Vail/Beaver Creek Seeding Program operated for the 2003-04 winter season through February 14, 2004. A total of 3,913.5 seeding hours were utilized throughout the operating season. The 2003-04 Seeding Season included 27 weather events over 62 calendar days.

The Denver Water Seeding Program over the Gore Range and in the Lower Blue and Williams Fork Basins ended on February 10, 2004 as scheduled. The adjacent seeding program to the west in the Upper Arkansas Basin continued through February 29, 2004. The portion of the Denver Water Program in the Upper South Platte and along the Continental Divide above the Upper Blue River Basin continued until the end of March 2004. March was a very dry month and only had two seeding opportunities. Both of these opportunities occurred with weather events having north-northwest winds.

The Denver Water Seeding Program operated on 29 weather events covering 77 calendar days for a total of 14,768 seeding hours. This was about 1,100 hours more that was estimated resulting from the abundant opportunities and moisture available in November and December 2003, and February 2004.

At the Colorado WDMP Midterm Project Review Meeting, Larry Hjermstad, the seeding contractor, stated that he had a few digital pictures of seeding generator sites that he would make available for possible inclusion in project reports. Larry subsequently emailed 12 digital pictures for such use. Figure 1 is an example of a generator site used for both the Vail/BC and Denver Water projects (see CSU website for site location).

Figure 1. WWC seeding generator site V1 (Ellison), elevation 7,088 ft, looking SE

Renaming of Generator Sites – During the Second Quarter, Greg Bryant (Denver Water GIS Coordinator) worked with Larry Hjermstad to finalize the renaming ice nuclei generator sites from initials of the operators to a numbering system. The result was an Excel spreadsheet that contains the site ID, location, elevation, status, and other information for all generator sites. This will be the official site-identification system for Denver Water and the identification scheme will be built into the research project's GIS and graphics. In mid-April, Greg emailed the final Excel spreadsheet file to all the project team. This spreadsheet file will also be posted on the CSU website. Ray McAnelly reports that CSU has been using the finalized generator location data correctly in their seeding runs.

WWC End-of Year (EOY) Final Seeding Logs – At the time of the April 14 project conference call, CSU had used the initial preliminary WWC seeding logs for about 8 seeding runs they had done. They found out during the call that there were updated logs, and they were then faced with figuring out if those seeding runs needed to be re-done with updated logs. But they were also faced with either updating their processed seeding logs with the changes, or processing the new logs again. Gustavo Carrió had spent considerable time processing the old logs (getting the data from the xls files and reformatted into a text file that serves as input to a pre-processing program that prepares the data for a seeding run), and he did not want to go through the same effort if it was easier to identify the changes and insert those changes into CSU's older processed seeding files.

To ensure that CSU was using the correct seeding log data, Ray McAnelly went ahead and processed the new seeding logs again, and in order to see how much they differed from the older logs (and to see to what extent CSU's seeding sensitivity runs might have been affected by the incomplete older seeding data), he made the comparison using CSU's older and newer text files (as opposed to doing it with excel software using the old and new xls files). Ray annotated the new text file with a brief comment documenting each difference between the old/new logs. Ray indicated that CSU has no problem concerning the EOY seeding logs, and they are now using the updated seeding logs for all seeding runs. After more sensitivity seeding tests, CSU decided to re-run all seeding cases.

GIS Seeding Dispersion Graphics Development - Using data provided by Ray McAnelly, Ross Williams has been working on the development of seeding dispersion graphics (as well as RAMS simulated 24-hr precipitation). The GIS map graphics are laid over the 2D terrain model Ross made out of 30-m DEM data. In the initial graphics, Ross included such items as the Denver Water Program's target area boundary, seeding generator locations, Snotel/Snowcourse sites, and country boundaries for reference. Figure 2 is an example of a seeding dispersion graphic, showing the 20-hr seeding simulation initialized at 0000 UTC January 2, 2004. The seeded material concentration is for the lowest model layer, or a 2D portion of the entire 3D field. The small bulls-eyes indicate maximum concentrations in the grid cells where the active seeding generators are located, and the more diffuse contours show how the collective seeding plumes have spread in the lowest model layer (mostly to the east due to the westerly wind).

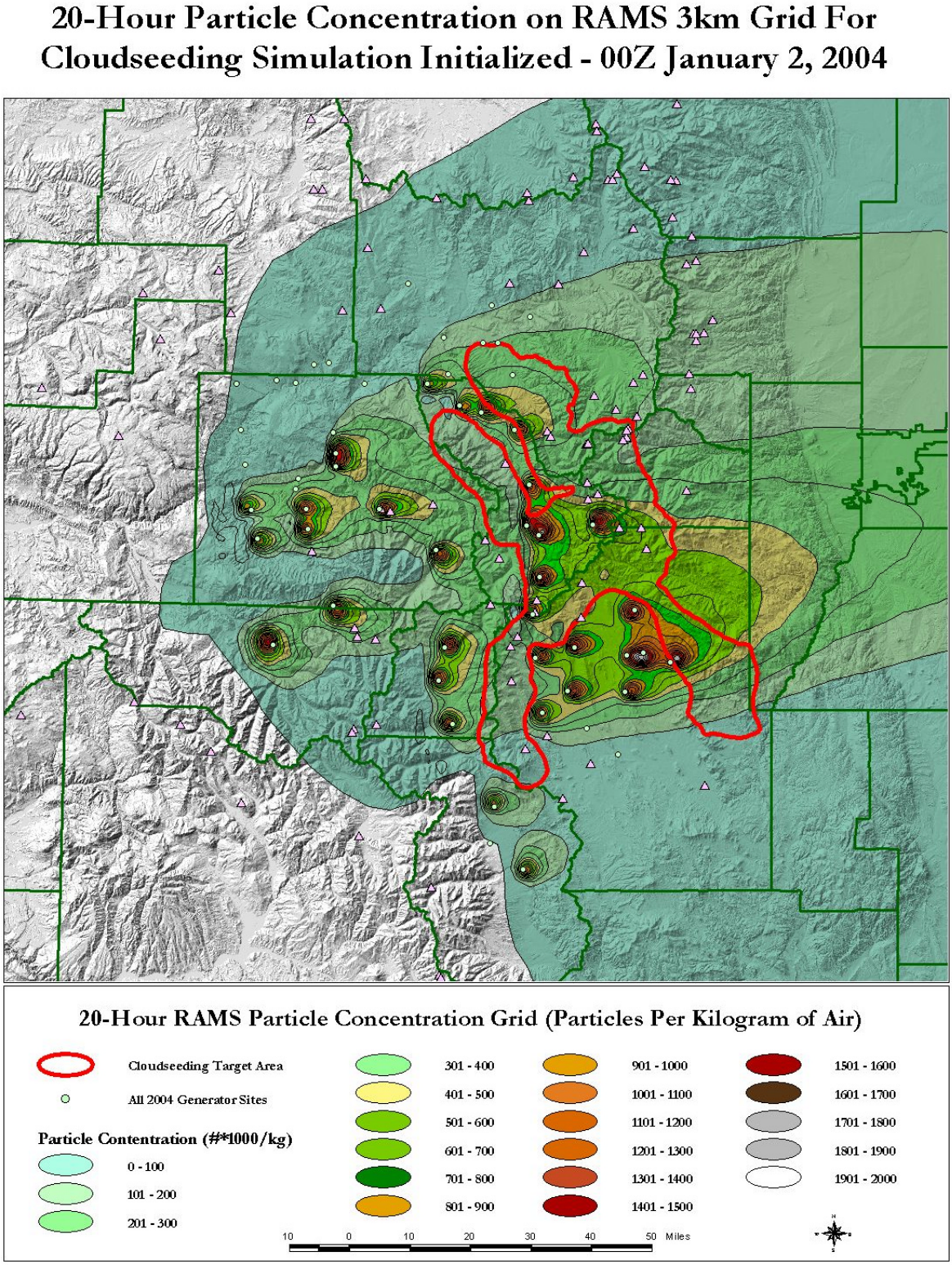


Figure 2. Example of a preliminary seeding dispersion graphic.

Project Performance and Status by Task

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

Deliverable 1 *– Graphic of RAMS grid over cloud seeding area with Snotel/Snowcourse sites, precipitation gages, and WWC ice nuclei generator locations (due December 15, 2003)*

This deliverable was completed and included on CSU's invoice #1 dated December 12, 2003.

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

Deliverable 2 *– Summary of changes to RAMS source code suitable for inclusion in reports (due December 15, 2003)*

This deliverable was completed and included on CSU's invoice #1 dated December 12, 2003.

RAMS Seeding Test Case from February 4, 2003 – This test case was completed by Ray McAnelly and Gustavo Carrió; the summary is attached at the end of this progress report.

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

Deliverable 3.1 *– Summary of procedures implemented for the automatic collection of meteorological data needed for decision making, including data type and location, and the establishment of a data archive (due December 15, 2003)*

This deliverable was completed and included on CSU's invoice #1 dated December 12, 2003.

Identification of all precipitation observation sites - The Snotel network is providing the bulk of precipitation data that will be used to evaluate the model's performance in simulating precipitation in control and seeding runs. This is due to its reasonably large number of stations at representative higher elevation sites over the entire study area, the reliability and generally high quality of its 24-hr precipitation and snow water equivalent (SWE) reports, and its uniform 0800 UTC reporting time for its 24-hr reports, which is convenient for evaluating 24-hr simulated precipitation. All Snotel sites in and near the seeding target area will be used in the evaluation, as well as a number of sites in other portions of the 3-km model grid. Since sites to the west and southwest of the Denver Water and Vail seeding operations may have been affected by other seeding programs, they will only be used for overall assessment of the model's precipitation prediction across the 3-km domain, and will not be used in the detailed evaluation of control vs. seeded simulations. For that evaluation, we will use sites in and near the target area and those basically north of Interstate 70. Final selection of sites to be included in the statistical evaluation will be done after quality control of the Snotel precipitation and SWE data, aided by comparison with data collected by NWS climate stations, ski areas, CoCoRaHS sites, and at snowcourse sites. During this evaluation, we may decide to include observations from

some of these other network sites in the statistical analysis, if their quality appears to match that of the Snotel data and if their non-consistent reporting times can be dealt with reasonably.

***Deliverable 3.2** – List of selected meteorological regimes (due March 31, 2004)*

This deliverable was completed and included on CSU's invoice #3 dated May 11, 2004.

A list of 30 days on which operational seeding was conducted was developed by Larry Hjermstad and Ray McAnelly; a meteorological regime was assigned to each of these 30 days. An evaluation day is from approximately 0700 UTC (0100 local time) of the DAY to approximately 0700 UTC of the next DAY - this approximately matches with a 24-hr Snotel observation with the date of DAY + 1. The list of 30 days with meteorological regime follows:

List of 30 DAYS for SEED/NO-SEED Model evaluation by CSU/RAMS

Date	Seeding time	Targeting wind	Wind Regime
1. Nov. 3, 2003	All 24 hrs	215 to 240 Deg.	Good SSW
2. Nov. 5, 2003	1100-0100 hrs	230 to 250 Deg.	Fair SW
3. Nov. 7, 2003	0830-0100 hrs	230 to 240 Deg.	Fair SW
4. Nov 10, 2003	0730-next hrs	250 to 260 Deg.	Good WSW
5. Nov 11, 2003	All 24 hrs	260 to 290 Deg.	Good WNW
6. Nov 14, 2003	All 24 hrs	240 to 270 Deg.	Good WSW
7. Nov 17, 2003	All 24 hrs	270 to 305 Deg.	Good WNW
8. Nov 18, 2003	Prev-1300 hrs	305 to 330 Deg.	Fair NW
9. Nov 22, 2003	0800-0100 hrs	230 to 305 Deg. Tropa	OK Tropa
10. Nov 25, 2003	0915-next hrs	260 to 275 Deg.	Fair West
11. Nov 26, 2003	All 24 hrs	275 to 325 Deg.	Good WNW
12. Nov 27, 2003	Prev-1400 hrs	330 to 350 Deg	Fair NNW
13. Dec. 8, 2003	All 24 hrs	220 to 360 Deg. Tropa	Good Tropa
14. Dec 13, 2003	0930-0100 hrs	300 Deg.	Fair WNW
15. Dec 15, 2003	All 24 hrs	340 to 360 Deg.	Good NNW
16. Dec 21, 2003	0800-0100 hrs	245 to 290 Deg. Tropa	Fair Tropa
17. Dec 26, 2003	All 24 hrs	210 to 260 Deg.	Fair Tropa
18. Dec 27, 2003	All 24 hrs	260 to 310 Deg. Tropa	OK Tropa
19. Dec 30, 2003	All 24 hrs	270 to 230 Deg. Trof Apch	Good WSW
20. Jan. 2. 2004	All 24 hrs	250 to 265 Deg.	Good WSW
21. Jan. 3, 2004	All 24 hrs	260 to 265 Deg.	Good WSW
22. Jan. 28, 2004	0700-0100 hrs	265 to 285 Deg.	Fair West
23. Jan. 29, 2004	Prev-1900 hrs	285 to 300 Deg.	OK WNW
24. Jan. 31, 2004	All 24 hrs	260 to 350 Deg. Tropa	OK Tropa
25. Feb. 4, 2004	All 24 hrs	310 to 350 Deg. Cl. Low>SE	Good NNW
26. Feb. 5, 2004	All 24 hrs	350 to 360 Deg.	Good NNW
27. Feb. 8, 2004	All 24 hrs	190-265-340 Deg Cl. Lo>SE	Like Tropa
28. Feb. 22, 2004	All 24 hrs	220 to 175 Deg. Trof Apch.	Good SSW
29. Feb. 24, 2004	All 24 hrs	175 to 240 Deg. Trof ->NE	Good SSW
30. Feb. 29, 2004	All 24 hrs	335 to 350 Deg.	Good NNW

There were eight meteorological regimes identified for the 30 selected days, as follows:

SSW wind –	3 days	
SW wind –	2 days	
WSW wind –	5 days	
W wind –	2 days	
WNW wind –	5 days	
NW wind –	1 day	
NNW wind –	5 days	
Tropa –	7 days	(Tropa = Trof passage)

Deliverable 3.3 *- Preliminary findings from the Langranian case study analyses (due May 31, 2004)*

Langranian Analyses – The Langrangian particle dispersion runs will be performed on several cases selected from the 30-day list.

Task 4 – ***Perform forecasts for seeded and non-seeded days.***

Deliverable 4.1 *– Copy of invoice for the procurement of additional PC processors needed to double the capacity of CSU's existing PC cluster (due December 15, 2003)*

This deliverable was completed and included on CSU's invoice #2 dated January 14, 2004.

Deliverable 4.2 *– Operational RAMS website containing full suite of products outlined in the WDMP RFP for the proposed research studies, and estimated precipitation accumulations for use in cloud seeding decision making (due December 15, 2003)*

This deliverable was completed and included on CSU's invoice #2 dated January 14, 2004.

The CSU cloud seeding website for this project (http://rams.atmos.colostate.edu/clseeding/) was operational from mid-December 2003 through March 2004, with very little downtime. This site was used to display daily realtime forecast products that were used to support the cloud seeding operations. Specifically, the daily runs were initialized at 0000 UTC (1700 MST), were run through 48 hr, and 2-hr products were displayed for the entire 0000 UTC cycle at http://rams.atmos.colostate.edu/realtime/00z/index.php3. Since seeding operations ended in March, the realtime forecast model has only been intermittently operational.

While the link to the "Realtime Forecast" was fully functional and current beginning fairly early in the operational cloud seeding season, development of the other links has lagged. For instance, the "Networks" link includes separate maps of the RAMS 3-km grid displaying the generator, Snotel and snowcoarse networks, but those for the CoCoRaHS, ski areas, and NWS climate/cooperative networks have not been finalized. At the "Data" link, only the complete list of Snotel sites has been posted, where 14 of the sites in and near the target area have been linked to the latest daily updated precipitation table at the National Resource Conservation Service

(NRCS) website. The on-line archive for "Daily Precipitation Map" has also seen limited development, with links only to precipitation maps generated from some of the sensitivity no-seed/seed experiments (including maps for control, seeded, and seeded-control precipitation). The delayed website development was primarily due to the problems with the realtime forecasts experienced in January-February and the realization that the entire season's worth of control simulations would have to be re-run.

After the problems with the realtime model were fixed, and after a sequence of seed/no-seed sensitivity runs led to a final simulation design, we are now in full production of consistent control and seeded simulations for the entire seeding season. While these runs are being completed through May and June, we will complete the development of the neglected links on the project website. This work will establish links to all observed precipitation data (Snotel, snowcourse, NWS climate/cooperative, CoCoRaHS, and ski area), and will post our quality-controlled precipitation data that will be used in the statistical evaluation. There will be a calendar-based method for displaying daily 24-hr precipitation maps from the original realtime run, the re-simulated control runs, and the seeding runs on days that had seeding operations. Maps showing the difference in 24-hr simulated precipitation between seeded and control runs will also be available. Daily observed precipitation maps will also be prepared for comparison with the simulated precipitation. Finally, there will be daily maps of seasonally accumulated precipitation (beginning November 1 - the start of the seeding season) for the seasonal set of control runs, for the set that includes seeding runs, and for observed cumulative precipitation.

In addition to the data links and daily precipitation maps, there is also ongoing development for links to project reports, project meetings and conference calls, for some of the GIS graphics produced by Ross Williams that includes RAMS output, for project-related presentations made at conferences and workshops, and for results of the evaluation and studies that will be completed.

Deliverable 4.3 *– Report on manually updated archive on RAMS website containing data from first and second model runs (due February 29, 2004)*

Use of PC Cluster for Realtime Runs - In the First Quarterly Progress Report (January 31, 2004), problems that became apparent in the realtime forecast model were discussed, along with the measures that were taken to remedy them. The problems became apparent as the season progressed deep into winter in January. They included too much low-level warming over high topography, unrealistic convergent flow into the elevated terrain on Grid 3 that developed in response to the warming, and over-predicted precipitation over the mountains that developed in response to the warming and convergent flow.

The problems were traced to three factors, two of which involved overly warm soil temperatures that resulted in too much surface sensible heat flux and low-level warming. The first of the two soil temperature problems was a model assumption that all soil moisture was liquid, which indirectly (through a soil thermal energy content relation) held the soil temperature at 0°C even when it should have been significantly colder (especially at higher elevations). The second problem with soil temperature was a model bug: even after fixing the previous problem by allowing soil temperature to initialize colder than 0°C, the bug resulted in a rapid warming of

cold soil temperatures (through the thermal energy content formulation) when the initial frost or frozen precipitation occurred on the topmost soil layer. Together these two problems resulted in soil temperatures that were too warm, especially at high elevations and deep into winter, and thus too much surface sensible heat flux and low-level warming at high elevations.

The third problem was an alternate horizontal diffusion scheme we had been using. This scheme had been used to avoid a runaway cooling problem that we had experienced the previous winter season when using the standard diffusion scheme, in which the regular scheme would sometimes produce a numerically unstable cooling trend at the surface in certain locations in steep topography in very cold (and especially clear) situations. However, the alternate scheme, while avoiding the runaway cooling, was not strictly mass-conservative, and it apparently contributed to the unrealistic mass convergence into the overly warmed higher elevations and the resultant over-predicted precipitation.

Three alterations to the model were made to remedy these problems: (1) allowing soil temperatures to initialize below 0°C (if the initial air temp is that cold) by assuming soil moisture is frozen; (2) fixing a surface-module bug that improperly allowed soil colder than 0°C to warm rapidly to 0°C when frost or frozen precipitation initially occurred; and (3) going to the default mass- and energy-conserving horizontal diffusion scheme (on all grids), combined with an alternate vertical diffusion scheme on the 3-km grid.

These problems and fixes were discussed in more detail in the First Quarterly Progress Report, after extensive testing had indicated that they should result in more accurate and reliable realtime forecast simulations. However, when these fixes were first implemented into the realtime runs on February 7, 2004, that first run saw a runaway cooling problem and model crash. Therefore, the fix 3 (above) was reversed for a few days while more testing was done.

Those tests showed that by increasing the lowest delta-z to 250 m (from the 150 m that we had been using), the runaway cooling problem did not occur with fix 3 for that same case (Feb. 7, 2004), nor for three subsequent cold-regime test runs. Thus fix 3 was re-implemented, along with the increased delta-z of 250 m, for the February 13, 2004 realtime run. That was a very cold situation, with the initial air temp at the lowest level ranging from -1 to -21°C on the 3-km grid. Although the run did not crash, there was still some runaway cooling that resulted in surface temps in the western valleys reaching as cold as -57°F during Day1 and -78°F on Day 2. So for the February 14 realtime run (still pretty cold regime), delta-z was increased to 300 m. A test showed it lessened, but did not eliminate, the excessive cooling problem in the previous night's run. As in that test, there was (slightly less) unreasonable surface cooling in the February 14 realtime run, but not catastrophic enough to crash.

Since then, there were no changes made to the realtime model – all fixes 1-3 were operative, with a delta-z of 300 m. No unreasonable surface cooling was noticed since the February 14 realtime run, probably due to slightly warmer regimes since then, warm enough not to trigger the problem. These fixes would likely work in re-runs of the entire winter and in subsequent winter seasons. Occasional exceptions might occur in extreme cold regimes after cold a continental-polar or arctic airmass sets in, with the possibility of slight or catastrophic runaway cooling. However, these occasions would generally occur with nearly clear and non-

precipitating regimes, where a degraded forecast or simulation crash would not be detrimental to a program focused on precipitation. The improvement in simulated precipitation due to these fixes should be apparent in the predicted precipitation fields in the realtime runs beginning in mid-February. This assessment will be possible through comparisons of observed 24-hr precipitation and the predicted 24-hr precipitation fields that are being readied for the project website.

Use of PC Cluster for Control and Seeding Runs - After the previously described fixes were made to the realtime model, it produced more reliable forecasts through the end of the seeding season. While the realtime simulations were intended to be the control or no-seed runs to pair with the post-event seeding simulations, the fixes made to the realtime model in February made it necessary to re-run the earlier realtime simulations in order to produce a consistent set of control runs. However, even the realtime runs after those fixes were made had inconsistent microphysical options with those that were necessary for the seeding runs, which would have made the evaluation of the sensitivity of seeding effects difficult because of these inconsistencies. Thus, due to the both the model fixes and the microphysical inconcistencies, it was determined that the entire season of realtime runs would have to be re-run in order to have a consistent set of control runs to evaluate against the seeding runs. In these consistent sets of runs, each pair of control and seed simulations would be set up identically except for the inclusion of seeded IFN and, upon activation, its contribution to pristine ice in the seeded run.

Initial control and seeding simulations were performed on several selected seeding events after designing such a consistent modeling framework. A typical result of the seed - control 24-hr precipitation field from these initial experiments is seen for November 3, 2003 in Figure 3. The difference field varies by up to about plus or minus 1 mm (the maximum 24-hr precipitation on the grid was about 72 mm in both simulations), and is organized into alternating (or adjacent) positive and negative bands that are approximately aligned with the 215 to 240-degree targeting wind that characterizes the event. Somewhat unexpectedly, the difference patterns affect a much larger area than the target area and downwind from there, with the bands extending across the entire mountainous portion of the 3-km grid, well upstream of the target area.

In an effort to better understand the extended-scale response to areally limited seeding such as seen in Figure 3, we performed a series of sensitivity tests in which one or more microphysical parameters were altered. Some of these parameters apply only to the seeded IFN and its activation, where changes in such parameters would not affect the control simulation, while others apply to the background IFN or to a hydrometeor type, where the choice for a parameter would affect both control and seeded runs. As we progressed through these sensitivity tests, some of the changed parameters were based on known factors as we became aware of them, and thus these changes were made permanent. For instance, Larry Hjermstad provided us with experimentally-derived increased activation rates of AgI at warmer temperatures that are due to the inclusion of moth balls (para dichlorobenzene) in the AgI solution that was burned by the seeding generators. Another permanent change was a slightly altered AgI activation dependence on supersaturation with respect to ice from a default linear dependence to a non-linear dependence found in the literature.

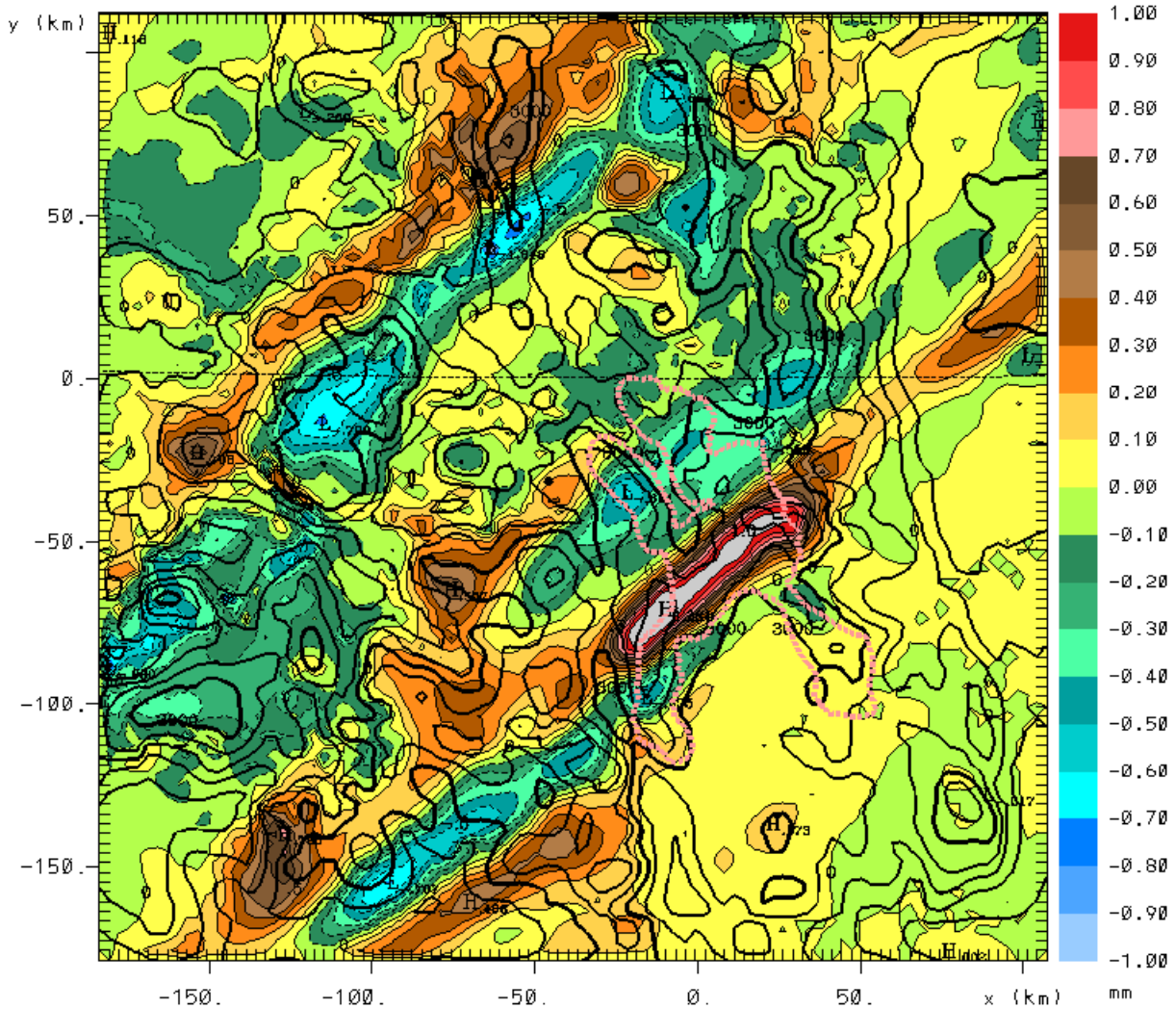
Choices for other parameters that we tested are more subjective, such as the number of IFN released per gram of AGI burned and the fraction of seeded IFN that is activated as a function of temperature (experimental data give a range of possible values for these parameters that varies by 1-2 orders of magnitude). Because of the unobserved and largely unknown background IFN concentration, we performed several sensitivity experiments in which the default concentration (which decreases with height largely as a function of density) was decreased to some fraction of the default field, and another experiment in which the background IFN was held constant (to disallow the transport of relatively high concentrations initially at low elevations to the initially low concentration regions over mountain ranges). We also tested the inclusion of a second cloud water mode with a larger drop-size distribution, which along with the regular cloud water mode provides a bimodal drop-size distribution.

Collectively, these experiments indicate that the 24-hr precipitation fields in both the control and seeding runs were affected very little by the choice for a particular microphysical parameter. The patterns and small magnitudes in precipitation difference fields between seed and control runs for a given sensitivity experiment in a given case were comparable to the those seen in other control vs. seed experiments for that case. They were also similar to the precipitation difference fields between pairs of control runs from two sets of sensitivity experiments (e.g., control runs with default background IFN concentration and with 50% of the default), and to the difference between pairs of seeded sensitivity runs for a case. The percent difference in seeded vs. control precipitation averaged over the target area is generally small in magnitude (<1%) and is as likely to be negative as positive. The percent differences are similar in magnitude over the entire grid and may be of opposite sign as that seen in the target area.

In most cases, particular southwesterly to west-southwesterly cases, the precipitation difference fields are small in magnitude (extrema of about 1 to 3 mm in magnitude) and are characterized by the banded structure aligned with the predominant wind as in Figure 3. An example from another case, January 2, 2004 is shown in Figure 4, where the bands are aligned with the 250 to 265-degree targeting wind in that case. In westerly to northerly cases, the banded structure is less pronounced and the precipitation difference extrema are very small. In cases with relatively strong embedded convection, the banded structure of the precipitation difference field is also not as evident, and the extrema may be considerably larger in magnitude in localities affected by the convection. For instance, a senstivity experiment for February 22, 2004, in which values for seeded IFN release rates and activation rates were set at the upper end of reasonable ranges, produced the largest magnitude of seeding response over the target area that was seen in all the experiments (Figure 5). The seeding response was -11.9% over the target area, indicating a relatively large suppressive seeding effect to the embedded mountain convection in that case. In general, however, the extrema in the seed-control difference fields are much smaller in magnitude and may be at locations far from the target area.

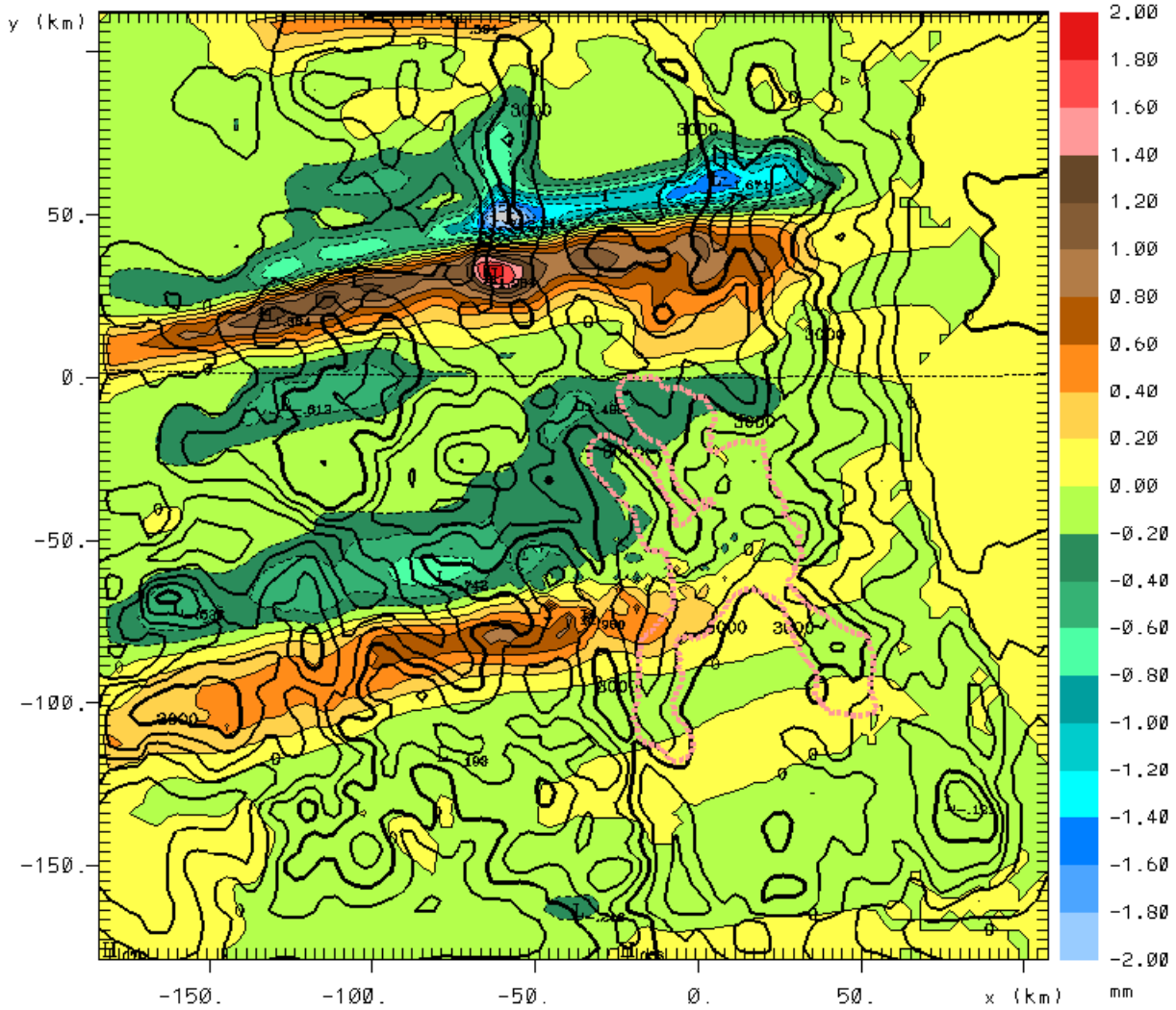
After performing these sensitivity tests, we have settled on the set of microphysical parameters that are now being used for the complete set of consistent control and seed runs. As these runs are being done, 24-hr daily precipitation maps will be posted on the project website for the original realtime runs, the final set of control runs, and the seeding runs for all seeded events. An evaluation of the original realtime run simulated precipitation against observed precipitation

will quantify the improvements made during mid-February. An evaluation of the re-run set of control runs will quantify its performance in simulating precipitation on daily through seasonal time scales. Finally, the control and seeded precipitation will be statistically evaluated against observations using the MRBP analysis code to assess the simulated seeding response.



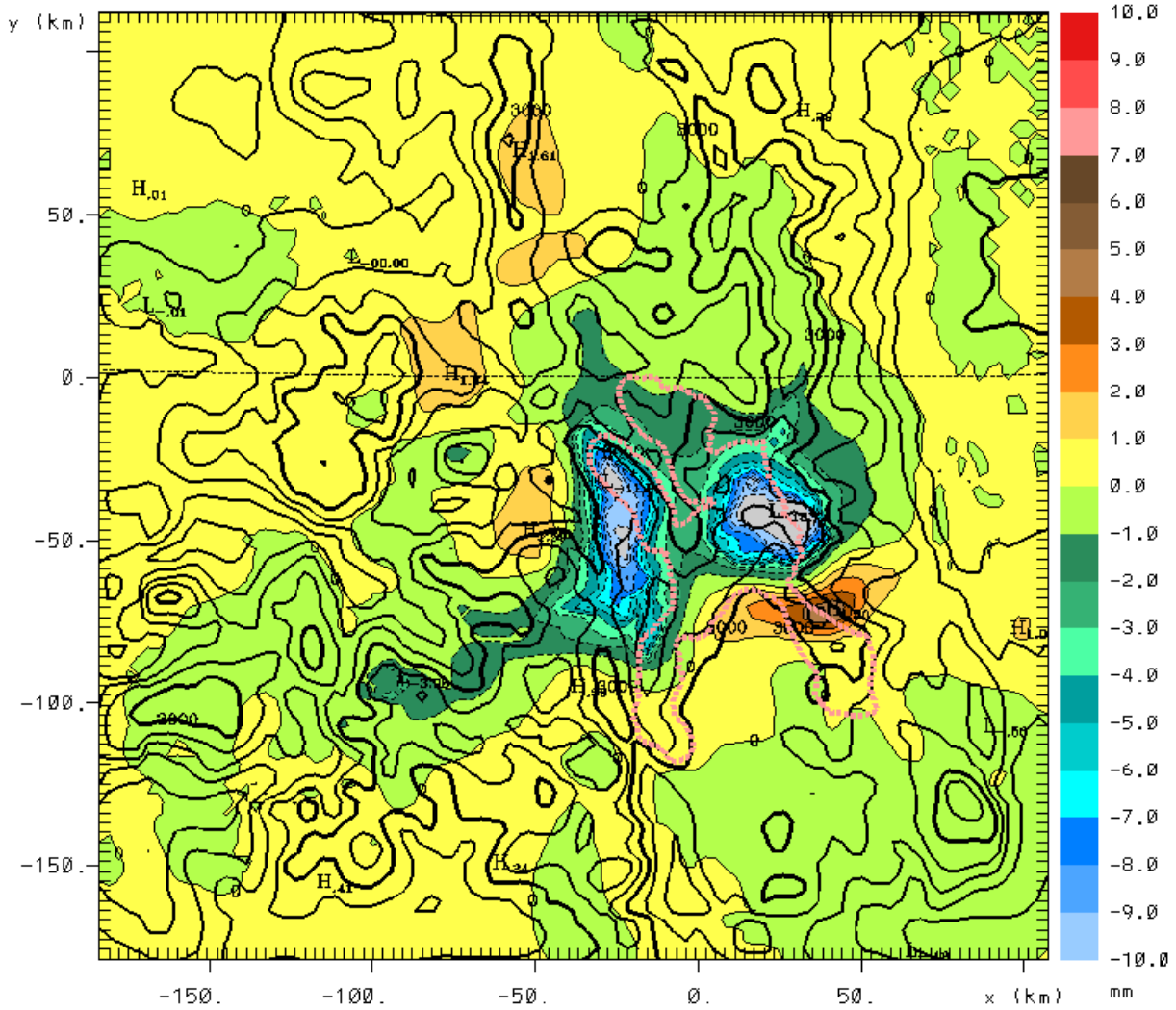
Init 11/03/03 0000 UTC seed		grid 3			
	2003-11-04-0800.00 UTC	min	max	inc	lab*
contours	sd-ctl precip 08-32h (mm)	-1.048	1.284	0.1000	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0

Figure 3. 24-hr precipitation difference field (seed - control) for an initial consistent set of sensitivity runs for November 3, 2003. Green to blue cool colors are negative difference; yellow to red warm colors are positive difference.



Init 01/02/04 0000 UTC sd6		grid 3			
	2004-01-03-0800.00 UTC	min	max	inc	lab*
contours	sd-ctl precip 08-32h (mm)	-2.214	1.984	0.2000	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0

Figure 4. 24-hr precipitation difference field (seed - control) for a set of sensitivity runs for January 2, 2004, featuring an unchanging concentration of background IFN.



Init 02/22/04 0000 UTC sd2		grid 3			
	2004-02-23-0800.00 UTC	min	max	inc	lab*
contours	sd-ctl precip 08-32h (mm)	-18.74	4.906	1.000	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0

Figure 5. 24-hr precipitation difference field (seed - control) for a set of sensitivity runs for February 22, 2004, featuring maximum specifications for seeded IFN release rates and its activation.

Deliverable 4.4 *– Quality controlled final archive on RAMS website containing lists of seeding operations and data from first and second model runs (due April 30, 2004)*

A series of factors, some described above under Deliverable 4.3, has delayed the production of control and seeding simulations that will be archived on the project website. These include the extended delay in acquiring the PC cluster and making it operational, the operational problems with the realtime model that required extensive testing and model fixes in late January to mid-February, some relatively minor delays in getting the seeding log data and subsequent updates, and the recently completed sensitivity testing of control vs. seeding simulations that was necessary to settle on the most reasonable and consistent set of microphysical parameters to be used for the production runs.

Control simulations are being run for the entire season, except for days where the original realtime runs and precipitation data indicate no precipitation fell. Seeding simulations are being run for all days that saw seeding operations, using the most recent updates for the seeding logs. The priority and timeline is to complete the control and seeding runs for all 30 of the selected days by the end of May, and the rest of the control and seeding runs by the end of June.

Precipitation maps for the control and seeding runs, for their difference (seed - control), and for the original realtime run will be posted on the project website as they are completed. The Snotel and other observational precipitation database will also be assembled, quality controlled, and posted on the website during the production phase of the simulations. The set of specific observation sites to be emphasized in the analysis and other details of the analysis methodology will also be developed during the simulation production phase.

Because of the factors stated above, the due date for Deliverable 4.4 needs to be slipped to June 30, 2004. This change will not effect the completion of the final report as current scheduled.

Task 5 – *Perform evaluations of model predictions of precipitation using MRBP.*

Deliverable 5.1 *– Copy of updated MRBP analysis code with documentation for users and selection of the month from the 2003-2004 operational winter season to be used in analysis (due March 31, 2004)*

This deliverable was completed and included on CSU's invoice #3 dated May 11, 2004.

A copy of the MRBP Analysis Code was provided by Dr. Paul Mielke, and the 30 cases that will be used in the analysis have been selected (see Deliverable 3.2).

The updated version of MRBP consists of two codes:

INPUT.f90: This code reads observational and simulated precipitation fields for a series of stations. These input files (obse.dat, reglr.dat, and seed.dat) are written in a free format matrix with rows and columns corresponding to days and stations, respectively. The number of stations (N_STAT) and the number of days to be considered in the test (N_DAYS) are input parameters. The code generates input matrices in the format needed by the MRBP analysis for RAMS standard simulations and for seeded runs (rglr_mrbp.in and seed_mrbp.in, respectively).

These files consist of a series of blocks corresponding to different test conditions. An example of the format of each block of the file that INPUT.f90 would generate for three stations and four days is given as a comment at the beginning of MRBP.f90. It must be noted that each block is preceded by a line that tests conditions.

MRBP.f90: This code computes the test statistic and associated P-value of a randomized block experiment. On the one hand, Dr. Mielke's original code has been translated from FORTRAN77 to FORTRAN90 (a more widely used version) and on the other hand, it was modified for this specific use. However, this program strictly follows Mielke's methodology. The program performs repeated MRBP analysis in one operation considering different input parameters such as alignment within blocks, distance function commensuration and rank tests (see Mielke, 2001). While running the program, it gives the user the option to compare the observation vs. the regular simulations or observation vs. the seeded runs and automatically selects the corresponding input matrix. The outputs for the comparison of the observation vs. the non-seeded and seeded runs are written in two text files: seed_mrbp.out and rglr_mrbp.out, respectively. The agreement measure, P-value, as well as the value of delta, its expected value, the variance and skewness are given for all above-mentioned options. As mentioned above, this code performs repeated MRBP analysis in one operation considering different test conditions and therefore the corresponding results are also written in each output file.

Note: The documentation for the revised MRBP analysis code as well as the listing of the two FORTRAN90 codes to be used for the statistical tests will be posted on the CSU website. It must be noted that this brief guide does not intend to describe the methodology associated with MRBP analysis that is explained in detail in Dr. Mielke's book *PERMUTATION METHODS: A DISTANCE FUNCTION APPROACH, Springer-Verlag, 352 pages.*

Deliverable 5.2 *– Preliminary results form the MRBP analysis (due May 31, 2004)*

Task 6 – *Research study supervision and reports.*

Deliverable 6.1 *– Draft technical progress report - First Quarter (due January 31, 2004)*

This deliverable was completed and included on CSU's invoice #3 dated May 11, 2004.

Deliverable 6.2 *– Draft technical progress report - Second Quarter (due April 30, 2004)*

This deliverable was completed and included on CSU's invoice #3 dated May 11, 2004.

Deliverable 6.3 *– Draft technical progress report – Third Quarter (due July 31, 2004)*

Deliverable 6.4 *– Draft Final Report (due October 31, 2004)*

Deliverable 6.5 *– Final Report submitted to US Bureau of Reclamation (due December 31, 2004)*

Appendix

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

We originally intended to use a seeding event selected from the 2002-2003 season as a test case for the model seeding code, in order to develop the code and have it ready when the 2003-2004 seeding data became available. Larry Hjermstad chose the February 4, 2003 seeding event for this test case and provided the seeding data. However, several factors delayed the test case experiment, including the delayed acquisition of the computer cluster, uncertainties in generator identification and location for the previous season, and our shifted priority to current season cases as those seeding data became available. Thus we have only recently (early May 2004) performed this test case study, where we used it as one of the seeding sensitivity studies discussed with Deliverable 4.3 in the Second Quarter Technical Progress Report. The primary sensitivity explored with this test case involved reducing the initial background or natural IFN concentration to 40% of that used in the standard code, for both control and seeding runs.

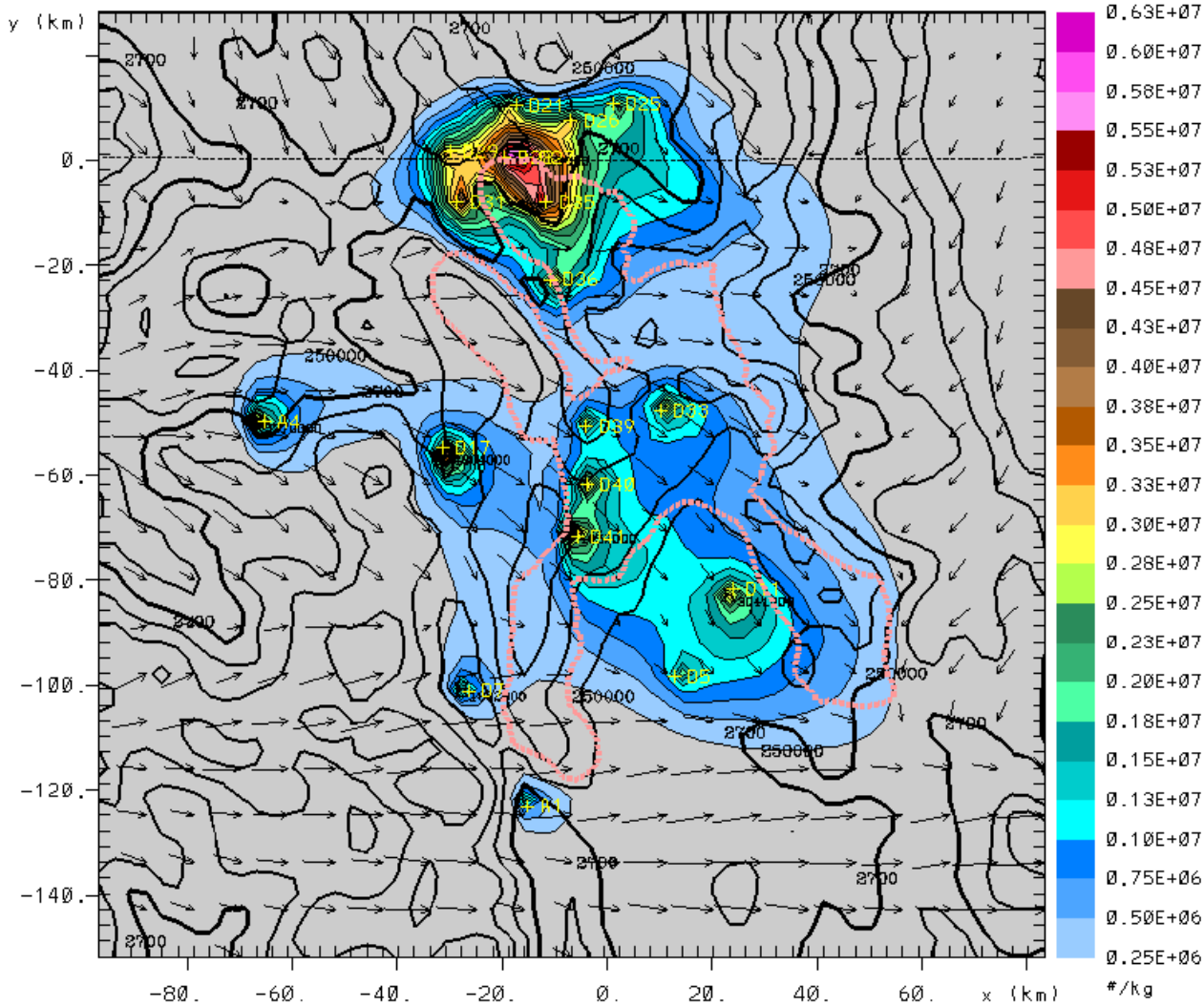
The test case simulations were initialized at 00 UTC on February 4, 2003 and were run for 36h to 12 UTC on February 5. From the seeding run, Fig. A1 shows the available seeded IFN concentration at the lowest model level at 24 hr into the run, well after all 19 of the generators used on this day had been activated. Only a portion of the 3-km fine grid is shown, zoomed into the target area. All 19 of the generator locations are marked, using the identifiers adopted for the 2003-2004 season. Generator D25 was deactivated for the latest season, and D5 was moved a few kilometers northeast from its 2002-2003 position in Fig. A1 for the 2003-2004 season. The other generators were at near-identical locations for the two seasons. The local maxima indicate the sources of seeded IFN in the 3 x 3 km grid cells that contain the generators. Much diluted concentrations are seen in the merged plumes that advect downwind toward the east and southeast.

Fig. A2 shows the vertically integrated concentration of activated seeded IFN, or pristine ice crystals that are nucleated on seeded IFN. The entire 3-km grid is shown. Two primary plumes are evident, one originating from the northern cluster of generators seen in Fig. A1 and the other from the southern cluster. A west-to-east vertical cross section in Fig. A3 is through the southern maximum seen in Fig. A2 and also through generator D11's location in Fig. A1. The black contours show the available seeded IFN concentration, with a surface maximum at the D11 generator location and extending upward and downwind in diffuse concentrations to about 3 km AGL. The color-contoured field is the activated seeded IFN (ice crystal) concentration, with a maximum activation region about 1.5 km over the crest of the Rampart Range. A similar plot of total pristine ice concentration along the same cross section (not shown) indicates the elevated band extending all the way westward across the domain, with the upstream portion due to nucleated background IFN. This main activation zone is between -20 and -25°C for both background and seeded IFN.

In the control run for this test case, the model setup is identical to the seeded simulation except that there is no seeded IFN. Simulated 24-hr precipitation on the 3-km grid from 08 UTC on February 4 to 08 UTC on February 5 is shown in Fig. A4. This period was chosen to coincide

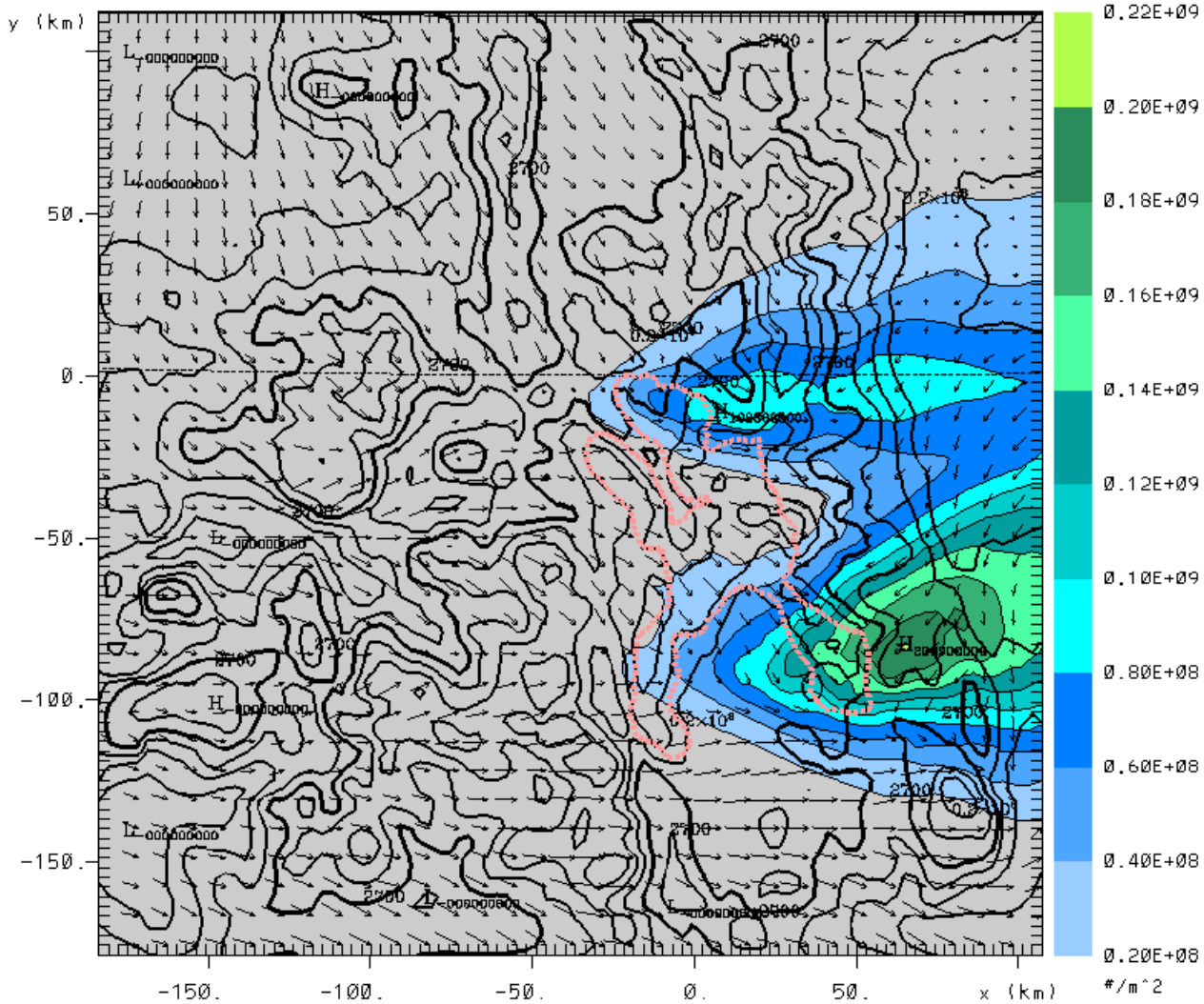
with 24-hr precipitation and snow water equivalent reporting times for the SNOTEL network. The first 8 hr of the seeding simulation allows ample time for any seeding material released early in the run to be transported over the target area and become microphysically active well before the 24-hr precipitation period. The control run shows precipitation maxima of about 15 mm along the western and northern ridges in the target area, with larger maxima to the west and particularly along the eastern flank of the northern Front Range. Very little precipitation is simulated at lower elevations. A cursory comparison with SNOTEL and CoCoRaHS observations suggests that the simulated precipitation is fairly accurate over the target area and much of the domain, but may be overpredicted by a factor of 2 or 3 along the Front Range maximum.

The corresponding 24-hr precipitation for the seeding simulation is not shown because it is almost identical to the control run. This is evident in Fig. A5, which shows the seeded - control 24-hr precipitation difference field. Very small positive and negative differences (<0.05mm) are organized into bands about 30-50 km wide, and aligned west-to-east along the prevailing westerly flow direction. This very small response to seeding is even less than the small response generally seen in other sensitivity runs (Deliverable 4.3). The domain-wide banded patterns are typical and indicate an unexpected seeding response, albeit very small, extending well away and even upstream from the target area.



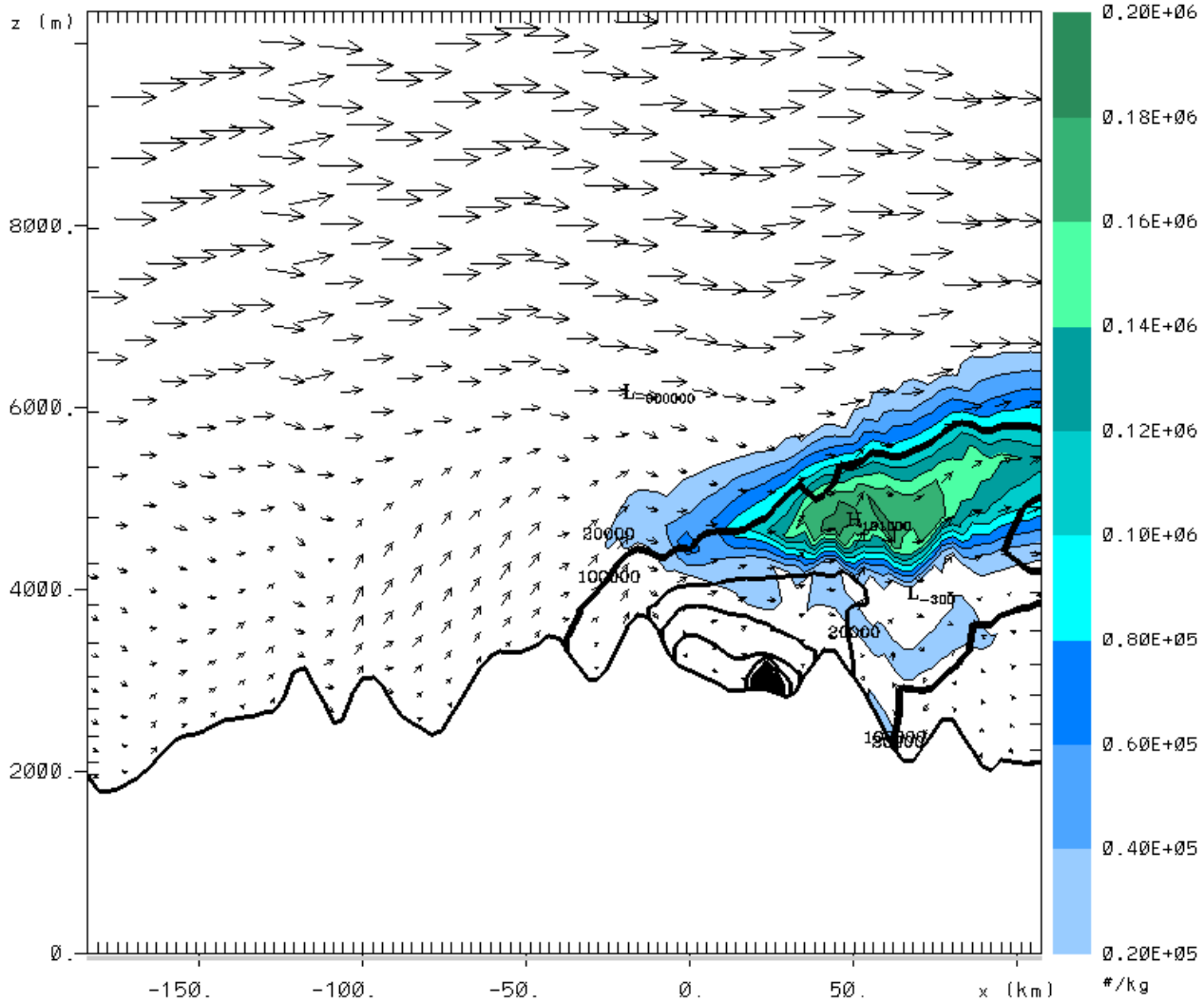
Init 02/04/03 0000 UTC sd4		grid 3			
z = 146.4 m	2003-02-05-0000.00 UTC	min	max	inc	lab*
contours	ifn2-conc (#/kg)	-7.198	0.6120E+07	0.2500E+06	1e 0
contours	topo (m)	1494.	3837.	300.0	1e 0
vectors →	3 m/s horiz	0.3034	12.34		

Fig. A1. Available seeded IFN concentration (color contours) in lowest model layer, zoomed in to the target area (peach colored dashed outline). Topographic contours (black) are at 300-m intervals, and wind vectors are drawn at every 3rd grid point. Generators are located at yellow plusses and labeled with the yellow identifier adopted for the 2003-2004 season.



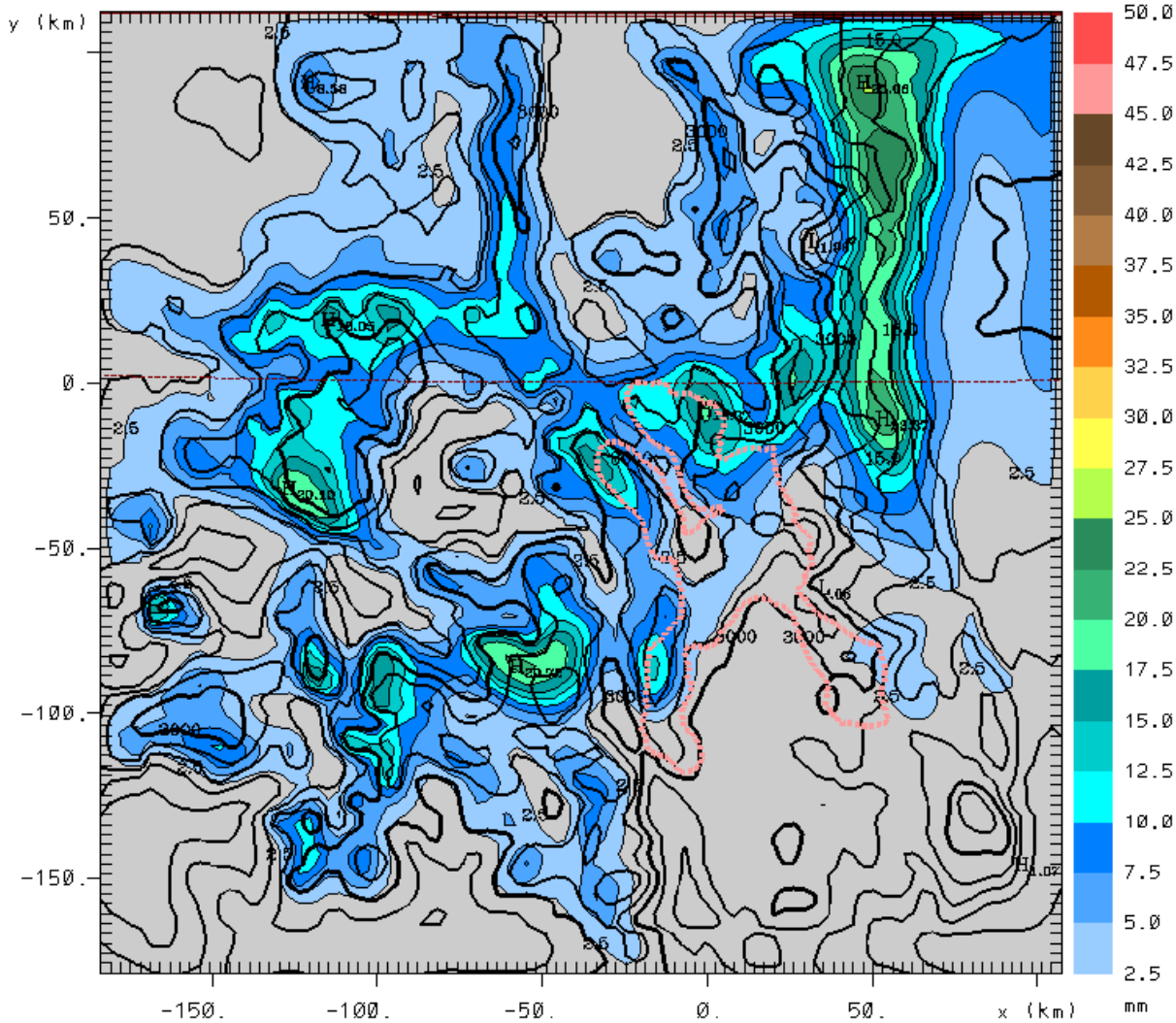
Init 02/04/03 0000 UTC sd4		grid 3			
z = 146.4 m	2003-02-05-0000.00 UTC	min	max	inc	lab*
contours	vertint act2 (#/m 2)	-1512.	0.2009E+09	0.2000E+08	1e 0
contours	topo (m)	1446.	3837.	300.0	1e 0
vectors →	3 m/s horiz	0.2063E-01	12.34		

Fig. A2. Vertically integrated concentration of activated seeded IFN (color contours) over entire 3-km model grid. Topography, wind vectors, and target area are as in Fig. A1.



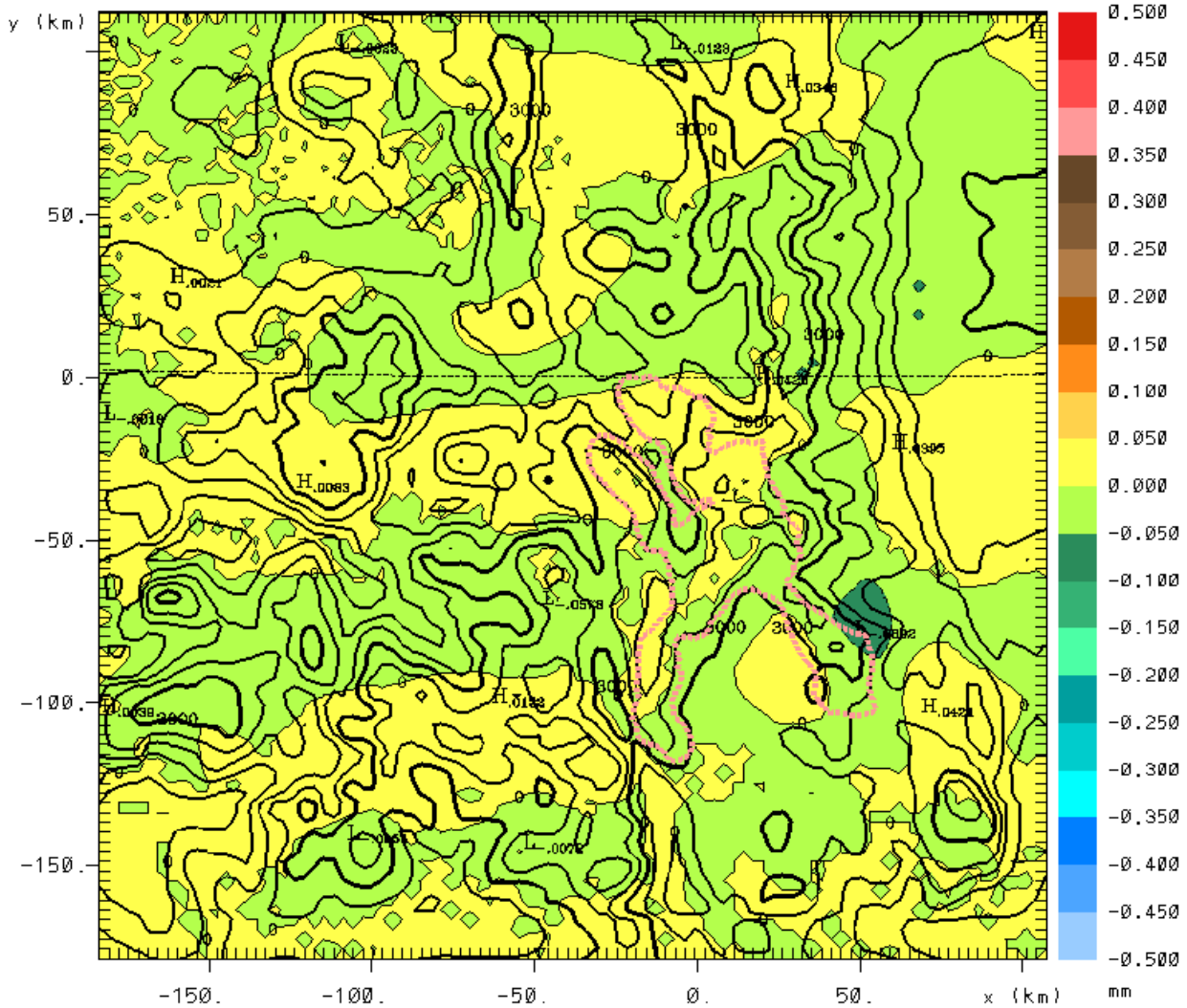
Init 02/04/03 0000 UTC sd4		grid 3			
y = −83. km	2003−02−05−0000.00 UTC	min	max	inc	lab*
contours	act2−conc (#/kg)	−305.3	0.1910E+06	0.2000E+05	1e 0
contours	ifn2−conc (#/kg)	−124.1	0.3041E+07	0.3000E+06	1e 0
vectors →	10 m/s horiz 0.36 m/s vert	0.8184E−01	49.00		

Fig. A3. West-to-east vertical cross section of activated seeded IFN (color contours) through the southern maximum in Fig. A2. Indicated are topographic outline, available seeded IFN (black contours beginning at 10^5 per kg and at 3x10^5 increments), and wind vectors.



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

Fig. A4. Simulated 24-hr precipitation for the control run.



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

Fig. A5. Seeded - control 24-hr precipitation difference field.