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

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Third Quarterly Technical Progress Report
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Overview of Project Status

On May 27th a Colorado WDMP planning meeting was held at Colorado State University (CSU) to review status of analysis-related deliverables that had not yet been completed. Joe Busto, Curt Hartzell, William Cotton, Ray McAnelly, and Brenda Thompson attended this meeting. Ross Williams participated in part of the discussions via a conference phone call. It was noted that four deliverables listed in the CWCB-CSU Interagency Agreement had to be delayed for reasons stated in previous quarterly technical progress reports. The CSU team was to continue work on Deliverables 3.3, 4.3, 4.4 and 5.2, while Ross Williams was to coordinate with Ray McAnelly on enhancing project area and production-run graphics for use in the final report. All Colorado WDMP project work is scheduled for completion by the end of Calendar Year 2004 as originally planned.

The Statement of Work in the CWCB-CSU Interagency Agreement listed 16 deliverables related to the six tasks; ten of these deliverables have been completed. These ten deliverables comprise about 68.3 percent of the CWCB-CSU agreement. However, considerable work was also done on four remaining data processing and analysis related deliverables (3.3, 4.3, 4.4 and 5.2). Work on these four deliverables is scheduled for completion during August and the first half of September. The remaining two deliverables (6.4 and 6.5) are drafting the final report and reviewing it with U.S. Bureau of Reclamation staff, and then finalizing the final report. The work completed during the third quarter of the Colorado WDMP is summarized in following appropriate subsections of this technical progress report.

Dr. William Cotton made a presentation at the 14th International Conference on Clouds and Precipitation (Bologna, Italy, 19-23 July 2004) on "A Winter Season Physical Evaluation of the Effects of Cloud Seeding in the Colorado Mountains Using RAMS." Co-authors for this paper were Ray McAnelly and Gustavo Carrió. The extended abstract for this presentation can be viewed on the project website at http://rams.atmos.colostate.edu/clseeding/. The abstract states that RAMS was used during the winter of 2003-04 to provide realtime forecast support for an operational cloud seeding program in the central Colorado Rocky Mountains. The objectives of related Colorado WDMP research studies include a better understanding of cloud seeding operations and the dispersion and interaction of seeding material with storms. As stated in the proposal, the goal is to provide a physical evaluation of operational cloud seeding in Colorado by using a well-established numerical model system.

Although the RAMS model was also extended to include seeding effects in order to evaluate the seed vs. no-seed precipitation simulated by RAMS, this study did not set out to prove or disprove if cloud seeding works based on RAMS model results. The reliability of model predictions of seed vs. no-seed differences depends not only on model simulations of the source strengths, transport and diffusion of seeding material, and its activation in clouds, but also on the natural background of ice forming nuclei (IFN). In this first year of the Colorado WDMP the study uses the Meyers formula for estimates of background IFN concentrations; however, experience has shown that there can be wide variations from estimates with this formula.

The comparison of RAMS simulated precipitation with observations from Snotel sites shows that the model significantly overestimates precipitation (see section on Deliverable 5.2). Dr. William Cotton commented on this in an email stating, "This (RAMS) is a fully coupled dynamic/microphysics/thermodynamics model and as such there is no opportunity for calibration of its behavior. Either the model is able to resolve the scales of motion that control natural or seeded cloud systems or it doesn't. With 3km grid spacing, the main limitation is not being able to resolve explicitly cumulus scales of motion. If embedded cumulus is important in the winter storms then they are not handled properly. We are developing and implementing a sub-grid cumulus scheme that fully couples to the microphysics that is very novel and different from what any other model has, but it won't be operational for a couple of years." So in addition to not having measured IFN concentrations to use in this study, the model's overestimates of simulated precipitation and inability to simulate precipitation from embedded cumulus clouds are other reasons that this study will not be able to confidently evaluate the seed vs. no-seed differences for the 2003-04 winter season.

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.

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.

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.

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

This deliverable has been delayed from the target due date stated in the Interagency Agreement between the CWCB and CSU for reasons stated in previous technical progress reports. However, this delay is not expected to effect the successful and timely completion of this Colorado WDMP project. The revised due-date for Deliverable 3.3 is August 31, 2004.

Lagrangian Analyses – The 30 days selected for detailed seed/no-seed evaluation were compiled and described in the 2nd Quarterly Technical Progress Report (Deliverable 3.2 - List of selected meteorological regimes). These 30 days span the full range of meteorological regimes that are conducive to snowfall in the project target area, and approximately six of these cases that are most representative of the regimes are being used for the Lagragian particle dispersion analysis. The control and seeding simulations for these 30 days have only recently been completed. The customized reruns for the six cases that are necessary for performing the Lagrangian dispersion analysis have been similarly delayed and will be completed during August 2004.

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.

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

This deliverable has been delayed from the target due date stated in the Interagency Agreement between the CWCB and CSU for reasons stated in previous technical progress reports. However, this delay is not expected to effect the successful and timely completion of this Colorado WDMP project. The revised due-date for Deliverable 4.3 is September 15, 2004.

Updated archive of data from 1st and 2nd RAMS model runs on CSU website - Based on the seeding logs, there were 86 days identified from the November 2003 through March 2004 that were affected by seeding operations. Since recently completing the control and seeding runs for the 30 selected cases, the pairs of control/seed simulations are ongoing and have been completed for about half of the remaining 56 days. These simulations, as well as the approximately six reruns for the cases selected for Lagrangian particle dispersion analysis, will be finished by the end of August. This timeframe is delayed about a month from what was indicated in the 2nd Quarterly Technical Progress Report, due to the cumulative effects of the factors discussed below under Deliverable 4.4. After completing all control/seed simulation pairs for the 86 seeding days, control-only runs will be performed for the non-seeding days during the seeding season, so that a full set of seasonal simulations can be evaluated against the full season of precipitation observations. These control simulations for the no-seed days should be completed by mid-September (simulations will not be needed for many no-seed days on which no precipitation was observed on the fine grid).

Preliminary results for the 30 selected days were recently presented by Dr. Cotton at the 14th International Conference on Clouds and Precipitation in Bologna, Italy, during the week of July 19-23, 2004. An update of this seed/no-seed evaluation and an initial analysis of model vs. observed precipitation for the 30 selected days are discussed below under Deliverable 4.4. The more detailed MRBP analysis of the model-predicted (control and seeded) and observed precipitation (Deliverable 5.2) will be performed During August.

Maps of 24h simulated precipitation from the control and seed runs are being linked to the project CSU website (http://rams.atmos.colostate.edu/clseeding/) as they are being completed. In addition, maps of 24h precipitation difference between the seed and control runs show the seeding effect. For comparison, precipitation maps from the original realtime forecast runs are also included on the website, in order to illustrate some of the operational problems discussed under Deliverable 4.4 and the modeling improvements that are seen in the after-the-fact control simulations.

The precipitation observations that are being used for the modeled vs. observed precipitation evaluation are also linked to the website. The daily gage-measured precipitation and snow-pillow measurements of snow water equivalent (SWE) at all available Snotel sites are the primary observations used for the evaluation, due to their daily consistency and uniform reporting times; the other observational networks are being used primarily to help quality-control the Snotel data. The data are presented by station in the raw format in which they were received, by station showing the quality-controlled daily values used in the evaluation, and mapped for each day in order to show the daily distribution of observations that can be compared to the simulated precipitation maps.

***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)*

This deliverable has been delayed from the target due date stated in the Interagency Agreement between the CWCB and CSU for reasons stated in previous technical progress reports, and another problem discovered during the 3rd quarter. However, this delay is not expected to effect the successful and timely completion of this Colorado WDMP project. The revised due-date for Deliverable 4.4 is September 15, 2004.

Quality controlled final data archive on CSU website - The full development of the project website has lagged the projected timeframe, primarily due to a series of problems that delayed the full production of the control and seeding runs. Most of these problems were described in detail in earlier progress reports and are briefly summarized here, followed by a description of a more recent problem:

1) An extended delay in acquiring the PC cluster and making it operational resulted in a much later startup of the seeding runs.

2) A later-than-expected receipt of the seeding logs for November, December and January contributed to the problem in (1).

3) The realtime forecast runs, originally intended to constitute the set of control runs for the entire season, became unusable for that purpose due to several problems that became evident deep into the cold season. The problems were traced to three factors, two of which involved overly warm soil temperatures that resulted in too much surface sensible heat flux and low-level warming. One of these was a soil initialization scheme that prevented the soil temperature from initializing colder than 0°C and the soil moisture from being initialized in frozen form, when those conditions should have been allowed at high elevations deep into winter. The second problem was a coding error with the thermal energy content applied to soil, where sub-freezing soil improperly warmed rapidly to 0°C when the slightest initial frost or frozen precipitation occurred in the topmost soil layer. The third problem was the use of an alternate horizontal diffusion scheme that we had used in previous winter seasons in order to avoid runaway cooling at the lowest layer that sometimes occurred with the standard diffusion scheme. The alternate scheme was not strictly mass-conserving, however, and in many runs it apparently resulted in too much mass and moisture convergence into the high country. When combined with the overly warm soil temperatures, these three problems

resulted in unrealistically warm low-levels and overestimates of precipitation in the mountains. As described in the 2nd Quarterly Technical Progress Report, these problems became noticeable about mid-January and persisted into February. The problems were solved by allowing the initialization of frozen soil moisture at sub-freezing temperatures; fixing the coding error in the thermal energy content formulation for soil; and switching back to the standard mass-conserving horizontal diffusion scheme, combined with a doubling of the low-level vertical grid spacing that generally prevents the runaway cooling that occurs frequently using that scheme with the original 150m vertical grid spacing.

4) After the problems in (3) were solved by mid-February, the realtime model forecasts improved significantly. However, as we began experimenting with the seeding runs, it became evident that even the improved realtime forecasts were unusable as control runs. This is because the model code that was developed to simulate seeding effects through a second IFN category was substantially different from the model code used for the realtime forecasts, with inconsistencies in microphysical options that made evaluation of subtle seed/no-seed effects difficult. Thus due to these inconsistencies and the earlier problems described in (3), it was determined that after-the-fact control as well as seeding runs would have to be performed for the entire season in order to get completely consistent pairs of control/seed runs, which differed only due to the introduction of AgI and its activation in seeding runs.

5) As described in the 2nd Quarterly Technical Progress Report, the initial sets of control/seed runs indicated unexpected seeding effects. There were very small differences in precipitation, and more unexpectedly, the patterns of the difference fields were generally organized into positive and negative bands aligned more or less with the mean wind and extending across much of the fine grid, far upwind and laterally from the target area. To further investigate these unexpected sensitivities before beginning the full set of control and seed production runs, a series of sensitivity tests were performed involving one or more of: the background IFN concentration; constant background IFN concentration fields vs. initial concentrations that could evolve through advection and diffusion; the number of IFN released per gram of AgI burned; several rates of AgI activation based on a range of empirically derived possibilities; and the inclusion of a second cloud water mode, which along with the standard mode provide a bimodal cloud water size distribution. These experiments all produced similar results regarding the small sensitivity to seeding on precipitation amounts and the large-area manifestation of these slight differences. After settling on a final, most suitable set of microphysical options based on these sensitivity tests, we began what we believed were the full production of control/seed runs in mid-May.

6) After finishing the control/seed runs for the 30 selected days and proceeding on through another dozen seeding days, another problem was discovered. The winds used to initialize the RAMS model and to provide time-dependent lateral boundary conditions on the largest grid are derived from NCEP's Eta model initialization and 3h forecast files. In the Eta files, the u and v wind components are relative to the Lambert-conformal mapping of the Eta grid, rather than being true u and v components. The model code used for the realtime runs had been adapted long ago to properly transform the Eta winds onto the RAMS grid. However, the different RAMS code that was used for the seeding development (see (4) above) had never been adapted to properly transform the Eta winds. The improperly transformed winds

are small in error and practically unnoticeable, except perhaps in the northern corners of the large domain where they can deviate from their true direction by as much as 30-degrees and thus be highly non-geostrophic. When this inadvertent error was discovered in early July, several cases were rerun with the corrected winds in order to assess the sensitivity to the error. The effects of the incorrect winds on precipitation amounts were trivial to moderate on the fine grid in the individual cases, but tended to produce more precipitation due to slightly incorrect large-scale dynamics being forced into the western boundary of the large grid. Because there is an over-prediction bias in the model as discussed in Deliverable 5.2, it was decided to rerun all the control and seed runs using the corrected wind transformation in order to eliminate this systematic error that exacerbated the problem. This error resulted in a further delay of three weeks in producing the final set of control/seeded runs.

These problems collectively have been a serious obstacle in developing the webpage with the final simulation results. Now that the runs are proceeding rapidly and smoothly, the webpage development will proceed accordingly.

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.

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

This deliverable has been delayed from the target due date stated in the Interagency Agreement between the CWCB and CSU for reasons stated in previous technical progress reports and in this report. However, this delay is not expected to effect the successful and timely completion of this Colorado WDMP project. The revised due-date for Deliverable 5.2 is August 31, 2004. The precipitation data that are needed for this analysis have been prepared, and the MRBP analysis will be performed during August. A simple initial analysis is described here based on the prepared data.

Preliminary results from the MRBP analysis - The observational data include daily precipitation and snow water equivalent (SWE) measurements made at Snotel sites in the network maintained by the National Resources Conservation Service (NRCS). The data obtained from NRCS consist of daily gage-measured precipitation expressed as a cumulative water-year total beginning October 1, and a daily measure of the SWE of the snowpack lying on the snow-pillow pressure sensor. Both measurements are to the nearest tenth of an inch and are uniformly recorded at 0800 UTC (0100 LST). The data sometime contain missing values for one or both parameters for a single or multiple consecutive days, but most of the sites have complete seasonal records of both parameters. The data occasionally indicate a non-physical negative precipitation increment, while more frequent negative increments in SWE can be real due to loss of snow to wind ablation and sublimation. A negative increment is assumed to indicate a zero daily increment for that parameter, and the greater of the two daily increments is assumed to represent the daily precipitation for that site. The SWE increment can be larger due to gage undercatchment in windy conditions, but also smaller due to loss of already fallen snow off of the snow-pillow (but not out of the gage) by increasing winds. We are still quality controlling this method of assembling a daily precipitation record for each site (based on consistency with nearby Snotel sites and precipitation observations from the other networks), but it appears to be reasonable. The original and processed data are being posted to the project website.

The simulations are initialized at 0000 UTC each day and are run out through at least 32 hours. Fields of 24h simulated precipitation are derived by subtracting the accumulated precipitation 8 hours into the run from that at 32 hours into the run, corresponding to the 0800 to 0800 UTC period of the Snotel observations. For evaluating control (non-seeded) vs. seeded simulated precipitation, the entire 24h precipitation field over the 3km fine grid can be used, focussing on the grid points laying in the target area boundary and in other areas of interest. For comparison with the Snotel observations, 24h simulated precipitation is extracted by bilinear interpolation at the Snotel locations from the four nearest grid points.

The total of the 24h precipitation fields from the control runs for the 30 selected days is shown in Figure 1. Local maxima are located over the elevated mountain barriers, with the Park Range in the north the West Elks in the southwest receiving the greatest totals (over 700mm or about 28 inches). Lowest amounts occur at the lowest elevations, both in the intermountain valleys and on the eastern plains. This distribution is consistent with the winter precipitation climatology in Colorado, suggesting that the model does reasonably well from a 30-day cumulative standpoint.

Of the 63 Snotel sites indicated in Figure 1, the derived 30-day precipitation record was complete at 61 sites. A plot of the 30-day total control-run precipitation extracted at these Snotel locations vs. the 30-day total observed precipitation is shown in Figure 2. Clearly an over-prediction bias is seen in the model, on average by a factor of 1.88. As indicated by the dashed line of best fit, the over-prediction factor is generally higher at lower-precipitation Snotel sites and lower at higher-precipitation sites. The correlation coefficient is 0.67.

A larger over-prediction bias and a smaller correlation results from using the set of control runs initialized with the incorrectly transformed winds as described in problem (6) in Deliverable 4.4 above. Similarly, the domain-averaged precipitation using the incorrect set of simulations is 10% larger than with the corrected set, and 4% larger averaged over the target area. While these differences are not severe, the improvements made by correcting that problem should justify the delayed production of the final set of runs.

The seeded simulations for the 30 days have been completed, and the evaluation of the control vs. seeded precipitation is currently underway. The simulated release of the seeded AgI is based on operational seeding logs, and its transport and dispersal appears to be realistic, as discussed and illustrated in the previous technical progress report. These simulations, combined with the ongoing Lagrangian particle dispersion analysis (Deliverable 3.3), will lead to a better understanding of cloud seeding operations, how the seeding material is dispersed, and the interaction of seeding material with storms. This greater understanding will be useful in improving future seeding operations.

An initial impression of the simulated seeding effects on microphysical processes and precipitation is that they are rather limited. This could be due to a much greater abundance of the natural or background IFN over the entire model domain, or to lower CCN concentrations, or inadequate representation of sub-grid-scale cumulus clouds. This assessment is only preliminary, however, as there are a number of difficulties in modeling and evaluating the complex microphysics in both the control and seeded simulations. A fundamental uncertainty is in the background IFN and CCN concentrations; since there are no operational observations of natural IFN or CCN, their initialization in the model is based on very limited experimental data and is independent of any actual synoptically related IFN distributions. Uncertainties in the activation properties of both natural and seeded IFN lead to further difficulties in realistically modeling the activation process. We are further evaluating the seed vs. no-seed differences in the model and its limitations in simulating these differences.

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)*

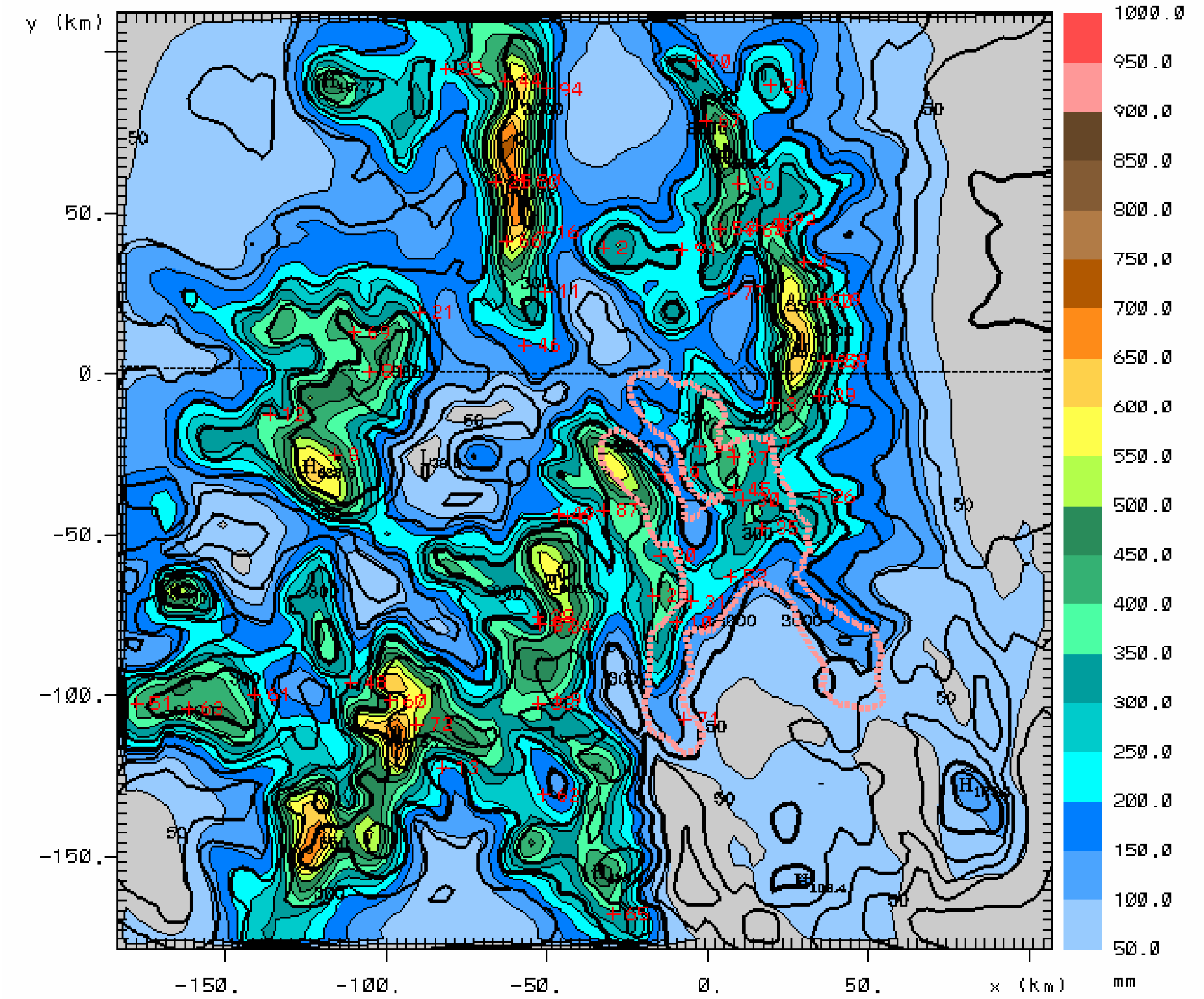
This deliverable was completed and included on CSU's invoice #3 dated May 11, 2004.

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

The submission of this technical progress report fulfills this deliverable.

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)*



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

Figure 1. Simulated control (non-seed) run precipitation on the fine grid summed over the selected 30 days. Color contours are at 50mm increments. Black contours are topography at 300m increments. The target area is shown by the dashed peach line. Snotel sites are indicated by the red plus symbols and labeled by the numeric identifier from the Snotel network on the project website.

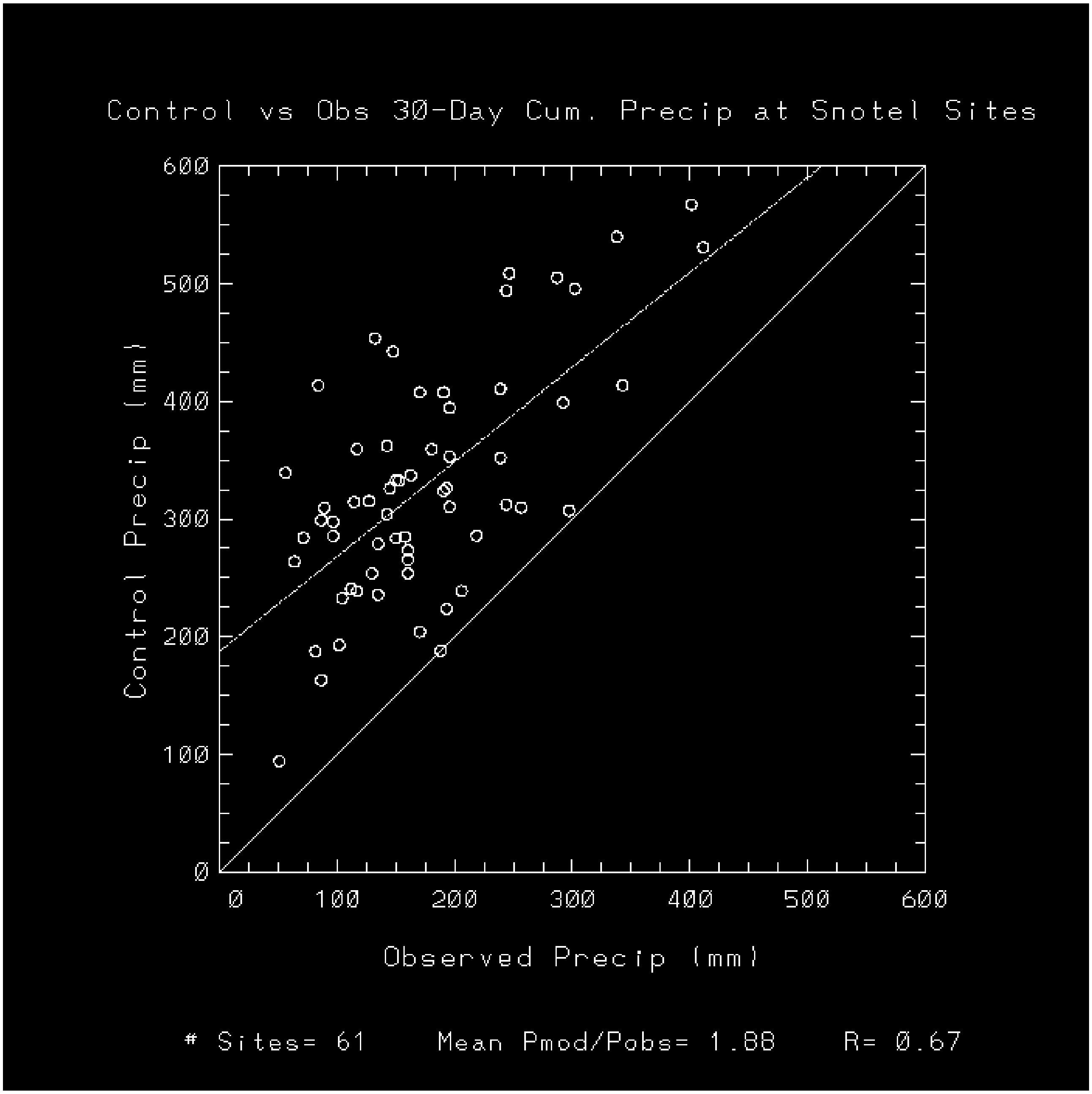


Figure 2. Plot of 30-day total control-run precipitation at 61 Snotel sites vs. the observed totals. The dashed line is the line of best fit.