COMET NWS Cooperative Project Final Report

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Type of Project (Partners or Cooperative):   Cooperative Project

Project Title:
Operational Use and Development of a High-Resolution Mesoscale Model in the Colorado Mountain Region for Wintertime and Other Forecast Applications

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Section 1: Summary of Project Objectives

        This COMET Cooperative Project was a collaborative effort involving faculty from Colorado State University (CSU) and the University of Nevada / Desert Research Institute (DRI), in partnership with the National Weather Service (NWS) Weather Forecast Office (WFO) at Grand Junction, Colorado (GJT). The primary objective has been to enhance operational forecasting procedures and techniques, through the use of a high-resolution mesoscale forecast model, for weather that significantly impacts public activities in the Intermountain West. Emphasis was placed on improved forecasting of phenomena related to winter storms, including quantitative precipitation forecasting (QPF), snow depth, blizzards, blowing snow, and icing conditions. The geographic focus area, northwestern Colorado, is a rural area in the WFO GJT area of responsibility which has had limited NOAA Weather Radio coverage and also has restricted radar coverage. A new Weather Radio transmission tower provides an opportunity to more effectively disseminate forecast information to the northwestern Colorado to demonstrate improved forecast benefit. The research goals also extended to the entire WFO GJT area.

        In conjunction with research and teaching activities at DRI's mountaintop Storm Peak Laboratory (SPL) located near Steamboat Springs, Colorado, collaboration between the CSU, DRI and GJT produced results from prior COMET projects, as well as from research sponsored by other agencies such as NSF, and outcomes of student field study projects, regarding mesoscale modeled QPF of snowstorms in the central Rocky Mountains.   The dual-university and NWS collaboration for the most recent COMET project has combined the specialized field facilities with advanced modeling capabilities to target improving snowfall QPF. CSU provided ongoing realtime

mesoscale forecast operations using the Regional Atmospheric Modeling System (RAMS). RAMS forecasts were made with a nested, regional 3km grid covering most of Colorado and southern Wyoming, including SPL. Model forecasts were made available for operational use at GJT and on the Internet for realtime use at SPL, and archived for post analysis. Additional post-event model simulations were made to test sensitivity of the snowfall predictions to parameters assumptions related to aerosol, microphysics and terrain forcing. The post-event simulations included the addition of a refined grid over the Park Range with grid spacing of 0.75km. The observational component of this project was based at SPL, and the GJT collaboration demonstrated improvement in operational forecast methods for snowfall QPF.

Section 2: Project Accomplishments and Findings

Operational field research was conducted during the winter periods of the project, based at the DRI Storm Peak Laboratory, a high-elevation research facility in the Park Range. Additional sampling sites and an NCAR Multiple Antenna Profiler Radar (MAPR) instrumented site at lower elevations nearby were established for an NSF-sponsored research project led by DRI and CSU in winter 2007 to investigate Inhibition of Snowfall by Pollution Aerosol (ISPA). Datasets are available at [http://www.eol.ucar.edu/rtf/projects/ispa2007].

Through the NSF-funded research project, DRI purchased a DMT Cloud Condensation Nucleus Counter (CCN) for measurements of cloud droplet active aerosol concentrations. The instrument is installed at the DRI Storm Peak Laboratory (SPL) and was operated for the winter 2006/2007 field studies. DRI also purchased two additional ETI high sensitivity snow water equivalent precipitation gages, one near the SPL to represent the upwind orographic precipitation measurement and one in North Park to monitor precipitation on the east side of the Park Range.

The COMET and NSF field studies were used as a focal activity for analysis, validation and sensitivity studies utilizing the CSU RAMS mesoscale prediction model. Realtime forecast products were operationally available [http://rams.atmos.colostate.edu/realtime/]. The RAMS model forecasts were used as guidance for initiating intensive observations periods as well as testing of operational snowfall prediction. Implementation of the microphysical binned riming scheme (Saleeby and Cotton, 2007) and use of more realistic fall speed velocities of snow crystals were incorporated into the realtime version of RAMS 4.3. These improvements in the model microphysics provided forecast guidance for onset of winter weather episodes. An internally computed snow depth prediction was made available as an output product. The realtime snow depth prediction is computed each model timestep from a snow density – ambient temperature algorithm developed by Simeral et al. (2006).

The Colorado State University - Regional Atmospheric Modeling System (RAMS) Version 4.3 has been utilized for a set of sensitivity simulations with varying amounts of cloud condensation nuclei (CCN), Giant CCN (GCCN), and ice forming nuclei (IFN) number concentration. For these simulations, the model uses a nested 4-grid arrangement centered over the Park Range in northwestern Colorado. The outer grid-1 covers the continental United States with 60km grid spacing (62 x 50 grid pts), grid-2 covers Colorado and the adjacent surrounding states with 15km grid spacing (54 x 50 grid points), grid-3 encompasses much of Colorado with 3km grid spacing (97 x 82 grid points), and grid-4 covers the north-south oriented Park Range from the cities

of Hayden to Walden with 750m grid spacing (114 x 114 grid points) (Fig. 1). Within each grid there are 40 vertical levels with a minimum of 75m vertical spacing. The model uses vertical grid stretching with a stretch ratio of 1.12 and a maximum vertical grid spacing of 750m. The 32km North American Regional Reanalysis data were used for model initialization and nudging of the lateral boundaries. A west-to-east vertical cross-section transecting the Park Range and centered on the Storm Peak Lab (SPL) (along the arrowed line in Figure 1) shows the model topography (Fig. 2) relative to SPL.

Saleeby and Cotton (2007) introduced a binned approach to riming within the bulk microphysics framework in which realistic collection efficiencies are used in the computation of collision/coalescence of ice crystals and cloud droplets. The hydrometeor gamma distributions are temporarily decomposed into 36 size bins for riming computations of all possible size interactions. This method is highly beneficial in winter orographic simulations, and is much improved over the bulk riming method which applied a single collection efficiency to the full size distributions. The hydrometeor fall speed computations were also updated based upon recent laboratory work. This significantly improved the estimated fall speed of snow and pristine ice crystals and reduced the disappearance of supercooled cloud water by reducing the Bergeron process.

Snow water equivalent (SWE) and snowfall depth measurements were collected in winter 2005 by David Simeral and Dr. Randolph Borys, and in winter 2007 by Dr. Melanie Wetzel with assistance by graduate students from CSU and UNR. Using support from this COMET project, David Simeral completed a Master's Degree from Northern Arizona University (while also working on the scientific staff of the DRI Western Regional Climate Center). His research characterized the relationship of snowfall density to air temperature and other local meteorological parameters measured in snow events over the Park Range. Mr. Simeral presented his results at the 73rd AMS Mountain Meteorology Conference in Santa Fe, NM (Simeral et al., 2006). His results supported previous analysis that was used to establish a temperature-dependant algorithm to estimate new snow density from ridge-top air temperature obtained from the RAMS model output.   Model output products based on this algorithm were produced operationally during the winter field season and used in conjunction with model evaluation.

RAMS model predictions of 24-hour accumulated SWE were generally good for the winter cases encountered during the Jan-Feb 2007 field measurement period (Fig. 3). Only those events which had manual SWE measurements made at the PHQ site within a 0-24 hr forecast period were utilized for this comparison. Two specific cases from February 2007 will be discussed, as these cases were also used to investigate hydrologic impacts of varying the concentration of cloud condensation nuclei, as will also be presented in this report.   Model output products for accumulated SWE and snow depth (Fig. 4) were assessed using gage and manual snow sampling measurements from several sites at varying elevation across the Park Range. Time series of precipitation measured at the Patrol Headquarters (PHQ) snow measurement site (along the ridge of the Park Range, close to the Storm Peak Lab site) shows close correspondence to the model products for the snow event of 11-12 Feb 2007 while the 23-24 Feb case indicates model underestimation of the precipitation amounts (Fig. 5 ; Fig. 6 ; Fig 7 [note that in Fig. 6 and Fig. 7, two consecutive daily accumulations must be added in order to determine the two-day snow event totals for the 11-12 Feb or 23-24 Feb periods]).

Dynamic and microphysical characteristics of the storm events contributed to the differences in snowfall production by these storms.   Time series from the NCAR MAPR instrument system for 11 February (Fig. 8) indicated relatively smooth west-northwest flow, and cloud sampling at the SPL site observed deep orographic cloud with high liquid water contents and near-continuous precipitation during the event. Observations made at SPL showed precipitation was dominated by warm crystal habits including needles and heavy rime on the crystals. High liquid water contents contributed to the large droplet sizes (>15 um diameter) in the presence of few CCN (<50 cm^{-3} droplet concentrations were observed). The RAMS model produced accurate simulations of the wind, temperature and humidity conditions within the system.   In contrast, the 23-25 February 2007 event (Fig 9) contained two strong wind shift events during the period 00-04 UTC on 24 February. This was accompanied by a sharp drop in temperature and with shallow cloud layer that was not well represented by the model. Low liquid water contents were observed at SPL with high droplet number concentrations (occasionally exceeding 230 cm^{-3}). Ice crystal riming was thus limited, and observed crystal type was primarily of unrimed dendrites.   In the operational mode followed for the use of the RAMS model forecasts during this field study, the model with the full resolution spatial grid was initialized each afternoon at 00 UTC and a reduced resolution model was started each morning at 12 UTC. Due to the specific timing of this event, it is possible that the model would have produced more accurate short-term forecasts of the storm dynamics and resulting microphysical conditions if run with full resolution each 12 hours. These case studies and the summary of precipitation comparisons indicate the need for continued use of real-time mesoscale models with ground-truth measurements in the winter storm environment.

The RAMS model has also been used to investigate the sensitivity of snow growth processes to changing concentrations of cloud condensation nuclei.   In each winter case, the CCN and GCCN concentrations were initialized as horizontally homogeneous with vertical concentration profiles that decrease linearly with height up to 4km AGL. Initial surface concentrations were varied from 100 to 1900 cm^{-3} for CCN and $1x10^{-5}$ to $5x10^{-1}$ for GCCN. The IFN nucleation rates were tested using a high rate (Meyers formula) and a low rate (DeMott formula based on observations from SPL). The aerosol concentrations are represented by a polydisperse field on a lognormal distribution with a median radius for CCN of 0.04μm. As a simple source/sink function, CCN are depleted upon droplet nucleation and replenished upon droplet evaporation. An ensemble of 36-42hr simulations were conducted for snowfall cases with the following start times and accumulated snowfall near SPL:

1200 UTC Feb 07, 2005 (Snow = 35cm)   **1200 UTC Feb 14, 2005 (Snow = 43cm)**
0000 UTC Feb 11, 2007 (Snow = 32cm)   **0600 UTC Feb 23, 2007 (Snow = 50cm)**

Total precipitation for a chosen ensemble member for each case is given in Fig. 10. These results come from the simulations with CCN = 100 cm^{-3}, GCCN = $1x10^{-5}$ cm^{-3}, and IFN = Meyers formula for nucleation. The obvious focus of precipitation is along the north-south length of the Park Range, showing increased accumulation with an increase in terrain height due to the orographic enhancement of snowfall. The domain precipitation maximum always occurs near the ridge-top, but the north-south location of the maximum varies among the simulations. This variation is likely due to variability in the direction of the mean wind and the degree of topographic blocking of the flow in the given cases.

For the Feb 14-16, 2005 case and Feb 11-12, 2007 we have compiled times series of SWE from the RAMS ensemble of simulations and nearby SNOTEL sites (noted on Fig. 10), as well as

periodic manual measurements of SWE at a station very close to SPL. These time series are plotted in Fig. 11, Fig. 12 and Fig. 13. The time series of the RAMS SPL grid point from Feb 11-12, 2007 (Fig. 11) display approximately an 8mm (~ 15-20%) spread in the final SWE totals among the ensemble with varying CCN, GCCN, and IFN concentrations. As a whole, the ensemble does well in prediction of the timing of precipitation onset and the precipitation rate for the duration of the event. The similarity in precipitation trend among the SNOTEL sites and RAMS suggests that this was a broad precipitation system with good spatial homogeneity over the southern Park Range. The Feb 14-16, 2005 event was more challenging for the model in terms of the orographic enhancement and possible downstream advection affects. Fig. 12 shows the SWE time series for several RAMS grid points relative to SPL; during this event the RAMS grid point closest to SPL under-predicted the snowfall. The best grid point match to the observations, and that relative to the SNOTEL sites, is the SPL+04 location that is 3 km downstream from SPL. If we examine the ensemble of simulations for the SPL+04 location (Fig. 13), we see a greater spread in the ensemble in this case with maximum final difference of approximately 12mm (~ 40-65%). When comparing these two cases, it is apparent that there is no consistent level of impact by aerosol variability, and it is very case specific.

To examine the impact of CCN on orographic snowfall near SPL, we plotted the total SWE along the SPL transect (Fig. 1 ; Fig. 2) for the clean and polluted CCN cases (Fig. 14). In each of the four cases the orographic enhancement of precipitation is quite obvious, but the point of maximum precipitation varies due to advection effects. The cases with stronger flow tend to advect the orographic snowfall farther downstream. Any additional condensate produced by strong vertical motion on the windward slope gets blown downstream before surface deposition can occur. The time series of wind speed at SPL from the observations and from RAMS simulations are shown in Fig. 15. The wind speed from the Feb 14-16, 2005 case is noticeably stronger than the other cases and the downstream shift in the orographic affect is, likewise, more substantial.

In each case, the increase in pollution aerosols results in the same trend; the snowfall on the windward slope is decreased while the snowfall on the leeward slope is increased. This blowover is a result of the modification of the orographic cloud properties by higher concentration of CCN. Note that since the Park Range is the Continental Divide, the effect of pollution aerosols is to shift precipitation from the Pacific watershed to the Atlantic watershed. The addition of CCN to the model simulation increases the cloud droplet concentration and reduces the mean droplet size. This, in turn, reduces the amount of riming by the reduction in collection efficiency between the snow crystals and cloud droplets. More lightly-rimed snow will have slower fall speeds which will result in surface deposition occurring farther downstream as the snow is continually advected horizontally by the cross-barrier winds. Another depiction of the pollution aerosol impact is shown in Fig. 16 as a plot of total precipitation difference due to an increase in CCN. From each of the four cases it can be seen that the degree of pollution impact varies among events. The Feb 7-9, 2005 and Feb 23-25, 2007 cases display only minor aerosol impacts while the Feb 14-16, 2005 and Feb 11-13, 2007 cases show substantial aerosol influence. When the influence is large and widespread, there is this consistent trend whereby the precipitation is reduced on the windward slope and deposited on the leeward slope. Though not shown here, there is a modest total reduction on the order of 1% in precipitation when one considers the total precipitation change of the windward and leeward slopes combined, but the largest impact is clearly a shift in water resources from one side of the Continental Divide to the other side.

The reason for case to case variability in the impact of pollution aerosol (CCN) arises from the variability in the presence and amount of supercooled orographic cloud water and strength of the winds above ridgetop. Since the primary pathway for CCN impact is through the formation of cloud droplets, then riming by snow crystals via the seeder-feeder process, this is the primary mechanism for precipitation modification. Without the orographic cloud, these hygroscopic nuclei are not efficiently utilized in a cold winter environment where cold cloud processes dominate. The last section referred to Fig. 16 that showed substantial CCN impacts only in the Feb 14-15, 2005 and Feb 11-13, 2007 cases. For comparison, plots of the event-averaged cloud liquid water content and ice mixing ratios are given in Fig. 17. A brief inspection of this plot reveals that the Feb 14-15, 2005 and Feb 11-13, 2007 events contained much more cloud water and/or a longer-lived orographic cloud. Thus, we expect a greater precipitation response to a higher concentration of CCN in these cases. The persistence and expanse of the orographic cloud in these cases is likely due to warmer temperatures (Fig. 18) and greater periods of saturation (see Fig. 19) as seen in the model and in the SPL observations. While there are some deviations between the model and observations at SPL in Fig. 18 and Fig. 19, the model closely reproduces the magnitude and trend in temperature and relative humidity in the majority of the simulation periods.

A second means by which the CCN concentration impacts mountain snowfall is in the type of precipitation that reaches the surface. As mentioned earlier, high values of CCN result in reduced riming. This reduces the mean mass of the snow crystals, reduces their fall speed, and reduces the formation of graupel (which would require heavy riming to convert snow to graupel). Fig. 20 displays cross-sections of cloud water and snow and graupel mixing ratio averaged over the duration of the events from Feb 14-16, 2005 and Feb 11-13, 2007. Only these two events are shown since they contain substantially more cloud water than the other two cases (Fig. 17). For each of the events Fig. 20 shows the averaged mixing ratios for the clean and polluted simulations. The major difference between the two is the amount of graupel that is present. The polluted simulations have less than half the averaged mixing ratio of graupel of the clean simulations as a result of the reduced degree of riming. This directly contributes to the downstream condensate blowover affect and spatial displacement of snowfall.

Additional improvements in the RAMS model physics were implemented during this project. RAMS and other models are often plagued by "runaway cooling" episodes as described by Poulos and Burns (2003). The CSU RAMS model now has the option of higher-resolution vertical grid spacing near the surface and more frequent updating of longwave and shortwave fluxes. In stable, non-turbulent conditions, model simulations sometime experience a compounding over-cooling effect at the surface if the model is unable to transport/diffuse surface air to higher levels where an inversion would typically form during overnight hours. Increasing the number of near-surface atmospheric levels as well as frequently calling the model's radiation routines tends to more appropriately create a nighttime inversion and prevent or reduce the effects of "runaway cooling". With the use of the Mellor-Yamada turbulent closure scheme, very stable conditions can underestimate the degree of PBL mixing. This can further aggravate the "runaway cooling" effect. We have implemented a function that offers a slight increase in the coefficient to the turbulent mixing length in stable conditions [coefficient increased from 0.75 (Andre, 1978) to 1.75 (per our experimentation)]. This prevents turbulent diffusion from shutting down in stable mountain valleys where we often experience the runaway cooling. Forecasted surface temperatures improved

following this modification. The implementation of higher vertical resolution provided improved forecasts of the Park Range orographic cloud in terms of cloud base height, cloud depth, and liquid water content.

The COMET project provided new forecast data products directly and derived from the RAMS model, and these were used for short-term operational forecasting by the Grand Junction WFO. The GJT staff (M. Meyers and others) also examined the snow density study results from Wetzel et al. (2004) and Simeral et al. (2006), for snowstorms during the latter half of the 2005/2006 winter season and during the 2007 winter season for their county warning area (CWA). The results of that analysis formed the basis for a snow accumulation Smarttool used in the Graphical Forecast Editor (GFE) by the GJT staff. Preliminary findings, which include the 2007 winter season, continue to show that the Smarttool performs well for colder events, where surface temperatures are below 0°C, and over the higher elevations (above 8000 feet MSL) of the western Colorado and eastern Utah. As could be expected, limitations were encountered for use of that particular technique for snowfall events over the lower elevations of the CWA, where surface temperatures were above freezing and the melting process was significant. During the 2007 winter season, several of these events occurred in mainly pre-frontal environments, where snow is the predominant precipitation category elsewhere. During the 2005/2006 season, under-prediction of the snow density occurred in deep closed-low events over the southern mountains of the CWA, where riming processes were occurring. Further evaluation and modifications are being made to the Smarttool to address these issues.

The hydrologic impact of the variation in the spatial deposition of snowfall is important both in terms of accumulated snow depth and magnitude of snow water equivalent that is produced in each storm event. As mentioned above, there is a small but quantifiable decrease in overall precipitation accumulation over the model domain due to a shift toward larger CCN concentrations. Moreover, the displacement of winter precipitation amounts between drainage areas and eastward across the Continental Divide (which crosses the model domain) can have significant import to the management and long-term resource expectations of the Front Range of Colorado as well as the entire Colorado River water management system.   One intended outcome of this project was to implement this type of merged atmospheric-hydrologic modeling. Although that component was not possible due to time and resource constraints, the RAMS model applicability to hydrologic model implementation is clearly indicated, and future research and development can provide this functionality. Another COMET project conducted by UNR/DRI and the NWS Forecast Office in Reno, NV demonstrated the combined use of radar and precipitation forecast datasets within a NWS GFE environment (Chew et al., 2005), and we recommend studies of that type to be conducted. The Park Range region is not conducive to that type of research due to the lack of adequate operational radar coverage (which was actually one of the motivating factors in improving mesoscale model applications for this COMET project), and other mountain regions such as the central Sierra would be more feasible. However, the Park Range and Storm Peak Lab facilities offer excellent opportunities for continued research on in-cloud processes related to snowfall forecasting and for testing of operational methods developed elsewhere for mountain meteorology.

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

Section 3: Benefits and Lessons Learned: Operational Partner Perspective

The GJT staff has benefited greatly from their interactions and visits to the Storm Peak Laboratory and with the scientists from DRI and CSU. We used the WES to examine case studies for the Park Range region. Having the detailed instrumentation has allowed us to fully investigate these types of winter storms. Some of these cases were used to satisfy the WES winter weather training requirements for the 2006 and 2007 seasons. A snow accumulation Smarttool was developed, and this enhanced the capabilities of the GJT forecasters to assess snowfall accumulation in both forecast and verification applications. As part of the project, two forecasters Joe Ramey and Ellen Heffernan conducted a familiarization visit at SPL which gave them hands-on experience of this mountain laboratory. On related research applications,the GJT SOO, Michael Meyers has also worked with the Center for Snow and Avalanche Studies in Silverton, Colorado to examine local mesoscale problems in the southwest that are crucial to supporting avalanche forecasting in the southwest Colorado mountains such as: forecasting storm snow water equivalent (SWE), precipitation intensity, new snow density, and the effects of rapid and/or prolonged warming and rain-on-snow events on snow morphology and snow climate. As part of the AMS Committee on Mountain Meteorology, he has contributed to a Monograph on Mountain Meteorology which will be developed during the summer of 2008.

Section 4: Benefits and Lessons Learned: University Partner Perspective

The data collection, modeling and analysis associated with the project has been valuable in providing more extensive evidence for the role of terrain, microphysical processes and ice/water nuclei in quantitative snowfall prediction. The project has also contributed to the involvement of multiple students in collecting observational data and making comparisons to mesoscale model simulations, which improves their awareness of NWS operational prediction activities and aiding their preparation for related careers. A graduate field course on Mountain Meteorology during January 2007 brought students from the University of Nevada, Reno (UNR) to Storm Peak Laboratory. The students developed individual research proposals that utilized some of the same instrumentation planned for combined COMET and NSF field projects. Graduate students from CSU also participated in these field programs and received training in mountain meteorology, snow observations, and model evaluations during CSU/DRI field course activities at SPL.

Section 5: Publications and Presentations

Hartzell, C.L., J. Busto, W.R. Cotton, R. McAnelly, G. Carrio, and L. Hjermstad, 2005: Numerical simulations of snowpack augmentation for drought mitigation studies in the Colorado Rocky Mountains. 16th Conf. on Planned and Inadvertent Weather Modification. American Meteorological Society, San Diego, CA. http://rams.atmos.colostate.edu/clseeding/workshops.html

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Saleeby, S.M., W.R. Cotton, R.D. Borys, D. Lowenthal, and M.A. Wetzel, 2007: Relative impacts of orographic forcing and pollution aerosols on mountain snowfall. *12th Conference on Mesoscale Processes*, American Meteorological Society, Waterville Valley, NH.

Simeral, David B., 2005: Spatial Variability of New Snow Density Across an Elevational Gradient in the Park Range of Northwestern Colorado. M.S. Thesis, Northern Arizona University, 97 pp.

Simeral, D.B., R.D. Borys and M.A. Wetzel, 2006: New snow density across an elevational gradient in the Park Range of Northwestern Colorado. Proc., *12th Conf. on Mountain Meteorology*, Amer. Meteor. Soc., Santa Fe, NM.

Wetzel, M.A. and R.D. Borys, 2004: Analysis of Valley Inversion Structure Using Radiosonde, Radar Profiler and Mountain mesonet data. *Eleventh Annual Workshop on Weather Prediction in the Intermountain West*, Salt Lake City, UT.
http://www.met.utah.edu/jimsteen/cirp/workshop2004/conference_program_04.html

Section 6: Summary of University/Operational Partner Interactions and Roles

National Weather Service: Michael Meyers (Co-Principal Investigator and supervised the NWS portion of the project, including NWS forecast briefings for the field project), Paul Frisbie, Jeffrey Colton, and Ellen Heffernan (assisted with data archiving and analysis), Norvan Larson (implemented and tested snow density algorithms for GFE Smarttools)

Colorado State University: William Cotton (Co-Principal Investigator, supervised the CSU portion of the project and participated in the field program and modeling studies), Steven Saleeby(carried out the modeling investigations), and Ray McAnelly(now retired from CSU carried out early realtime modeling applications and downloaded data to the USGS hydrological model).

Desert Research Institute: Randolph Borys (Co-Principal Investigator and director of Storm Peak Lab; development of field operational plan for DRI component of project and management of SPL measurement systems), Melanie Wetzel (Co-Principal Investigator; acquisition of snowfall datasets and analysis of case study meteorology), Douglas Lowenthal (collaborating faculty member from DRI; analysis of aerosol and cloud physics measurements), David Simeral (field scientist; field measurements of snowfall and interpretation of snow density case studies), Ian McCubbin (graduate student; field measurement support).
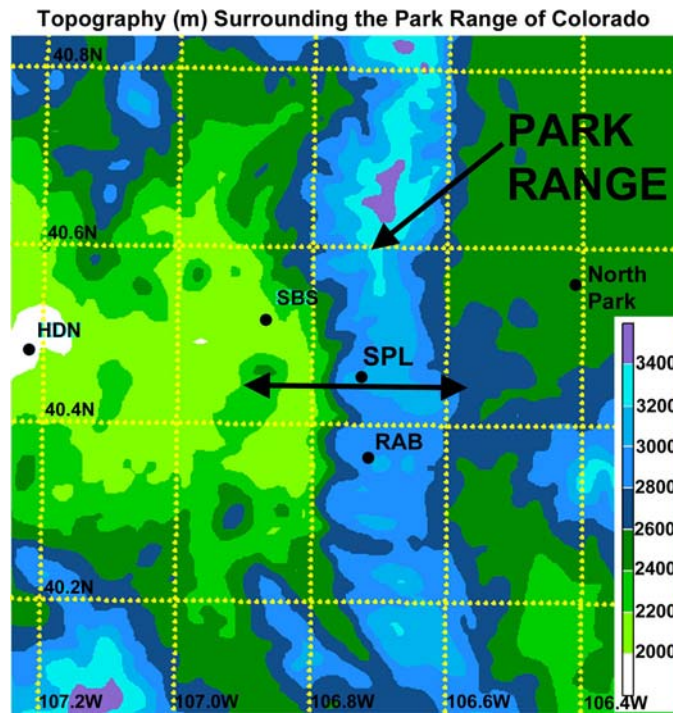
Figure 1. RAMS Grid-4 with grid spacing of 750m. Color contours indicate surface elevation (m). Locations of Hayden (HDN), Steamboat Springs (SBS), Storm Peak Lab (SPL), Rabbit Ears Pass (RAB), and North Park are labeled for reference. The bold-horizontal line depicts the cross-section range in Fig. 2.
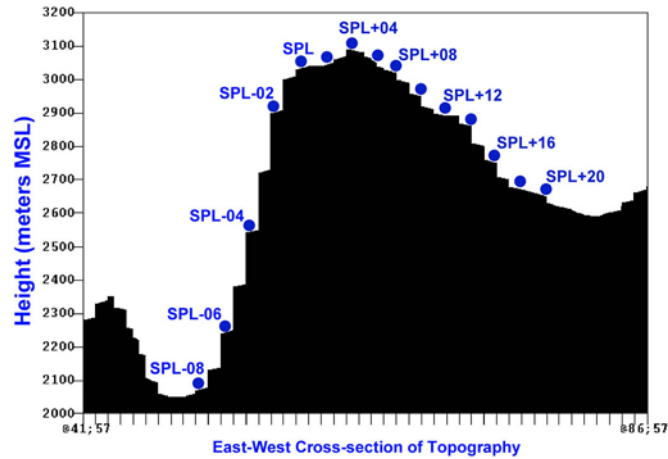
Figure 2. West to east model topographic cross-section centered roughly on SPL. Blue dots depict location of horizontal grid points, such that "SPL+04" is 4 model grid points east of SPL. Cross-section location is shown by the horizontal, bold, arrow-tipped line in Fig. 1.
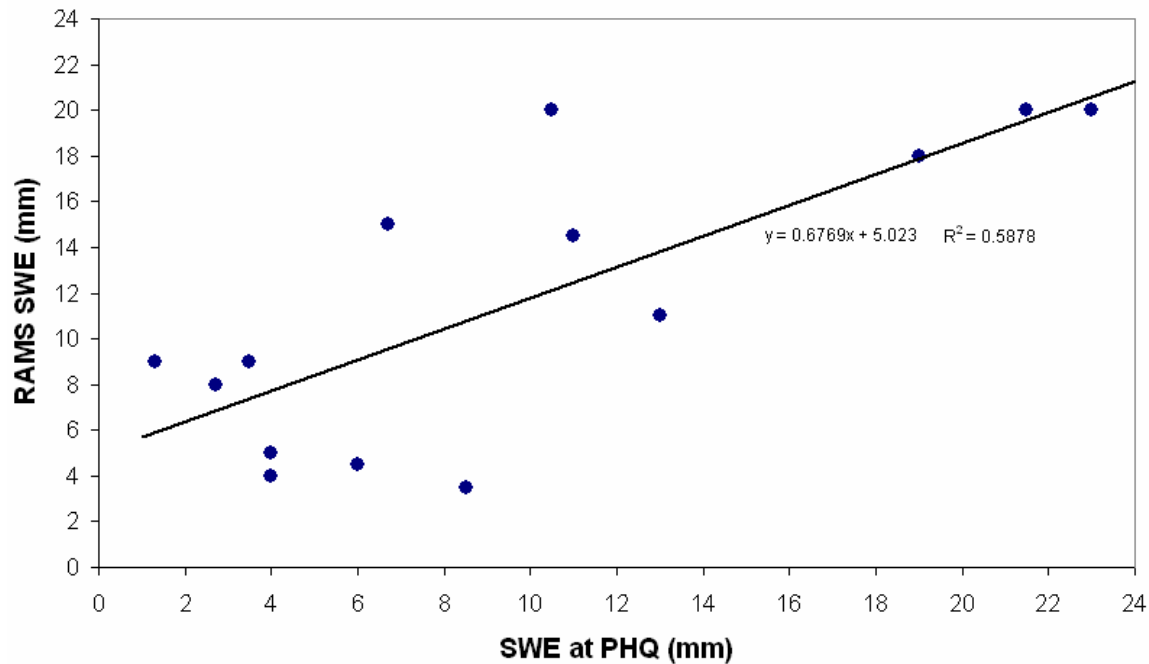
Figure 3. Comparison of snow water equivalent (SWE) predicted by the RAMS model from 24-hour simulation periods and measured at the Patrol Headquarters (PHQ) site during January-February 2007.
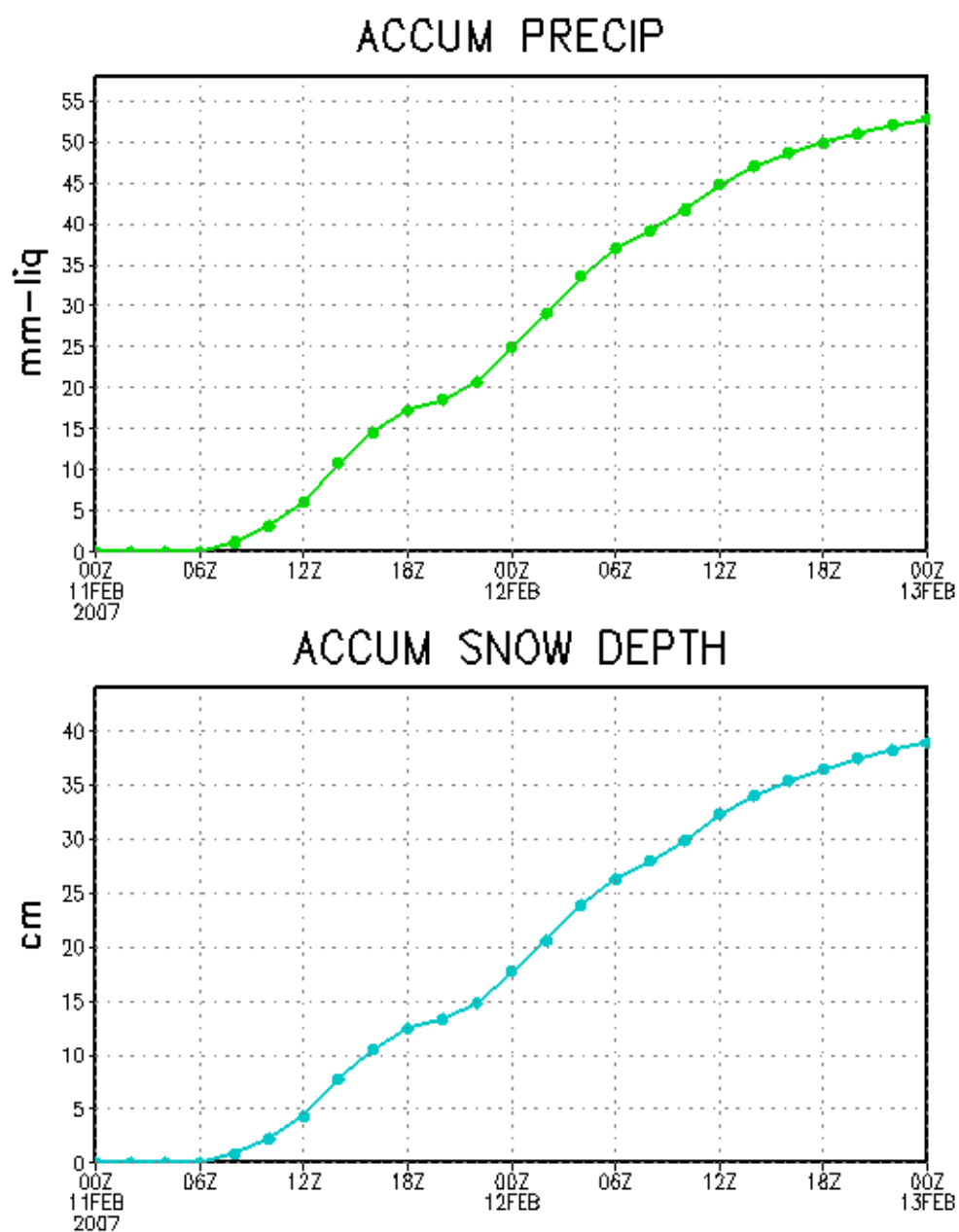
Figure 4. Example of the RAMS forecast products for time series of precipitation accumulation (cm) and snow depth (mm) used during the winter field project.
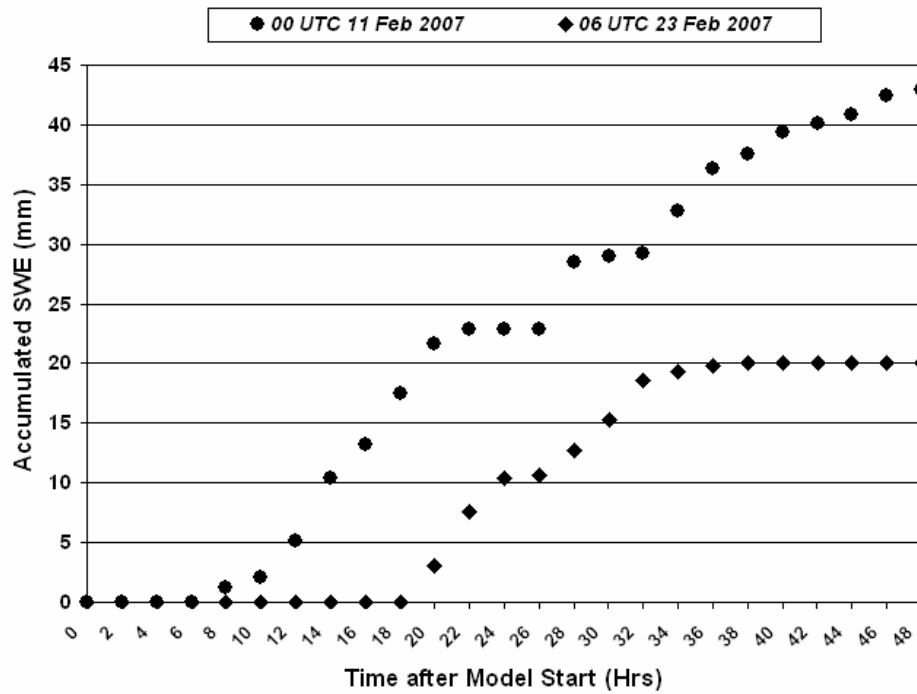
Figure 5. Time series of predicted SWE accumulation during two RAMS simulations from February 2007.
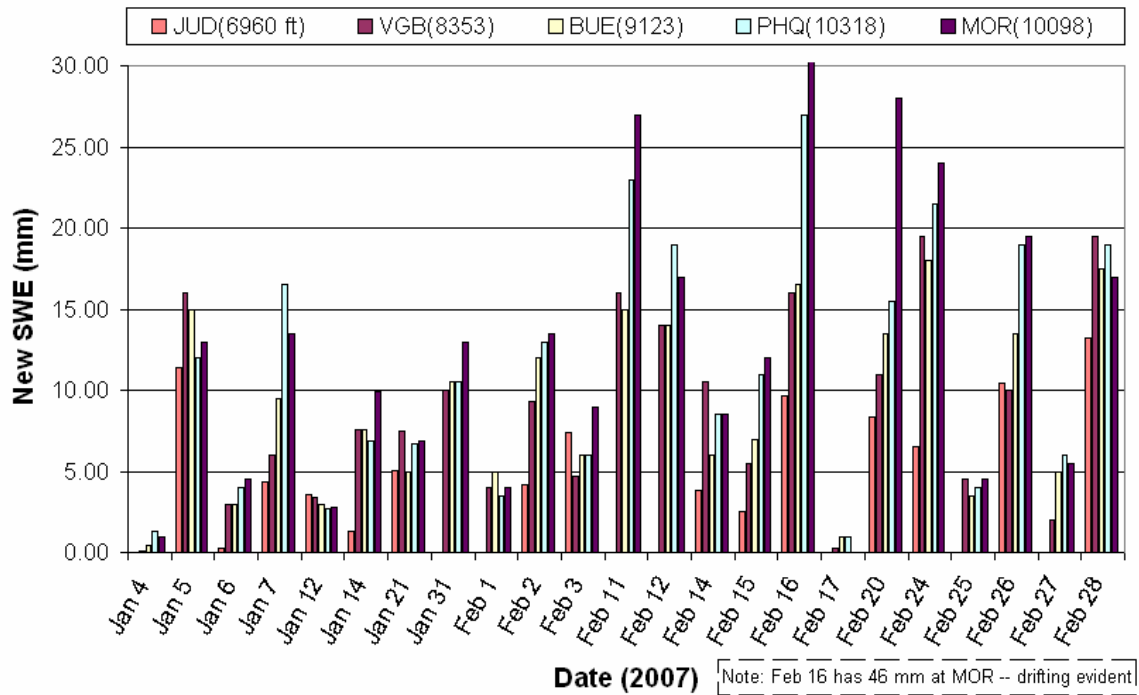
Figure 6. SWE accumulations at five sampling sites (elevation shown) during early 2007.
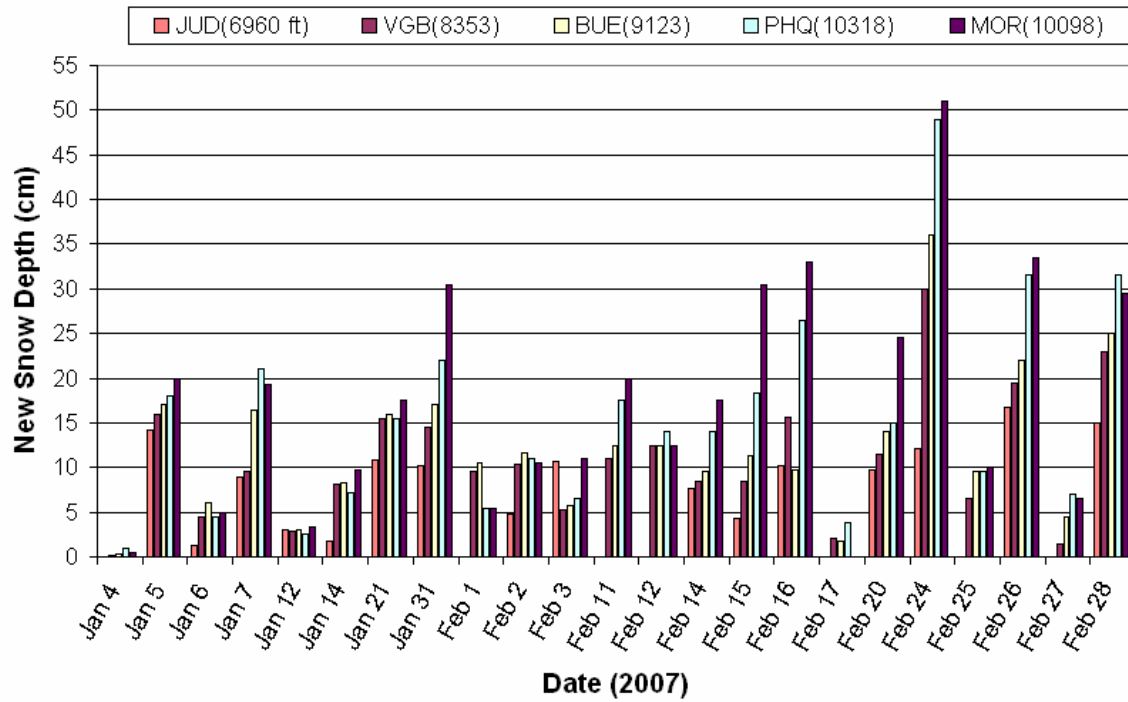
Figure 7. Snow depth accumulations at five sampling sites (elevation shown) during early 2007.
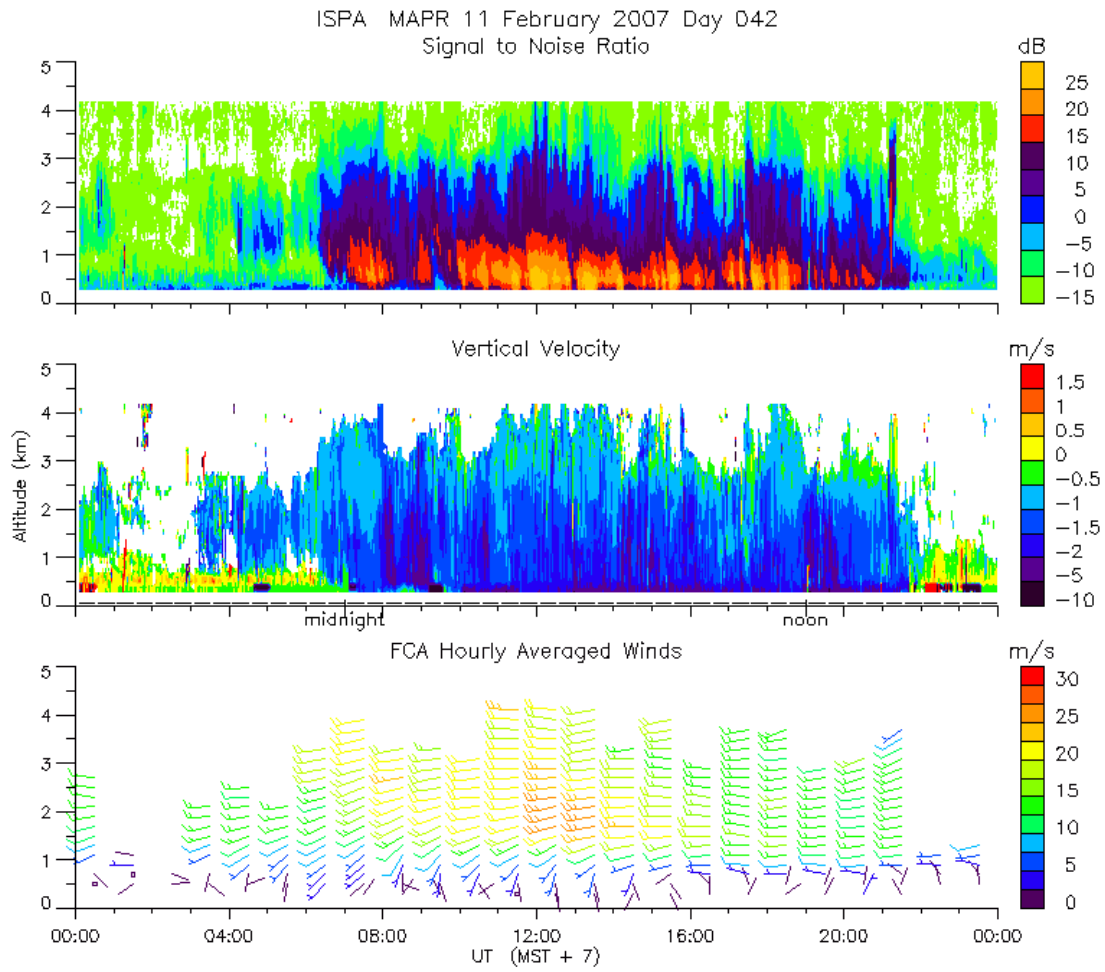
Figure 8. 11 Feb 2007 time series of NCAR MAPR precipitation, vertical velocity and wind profiles.
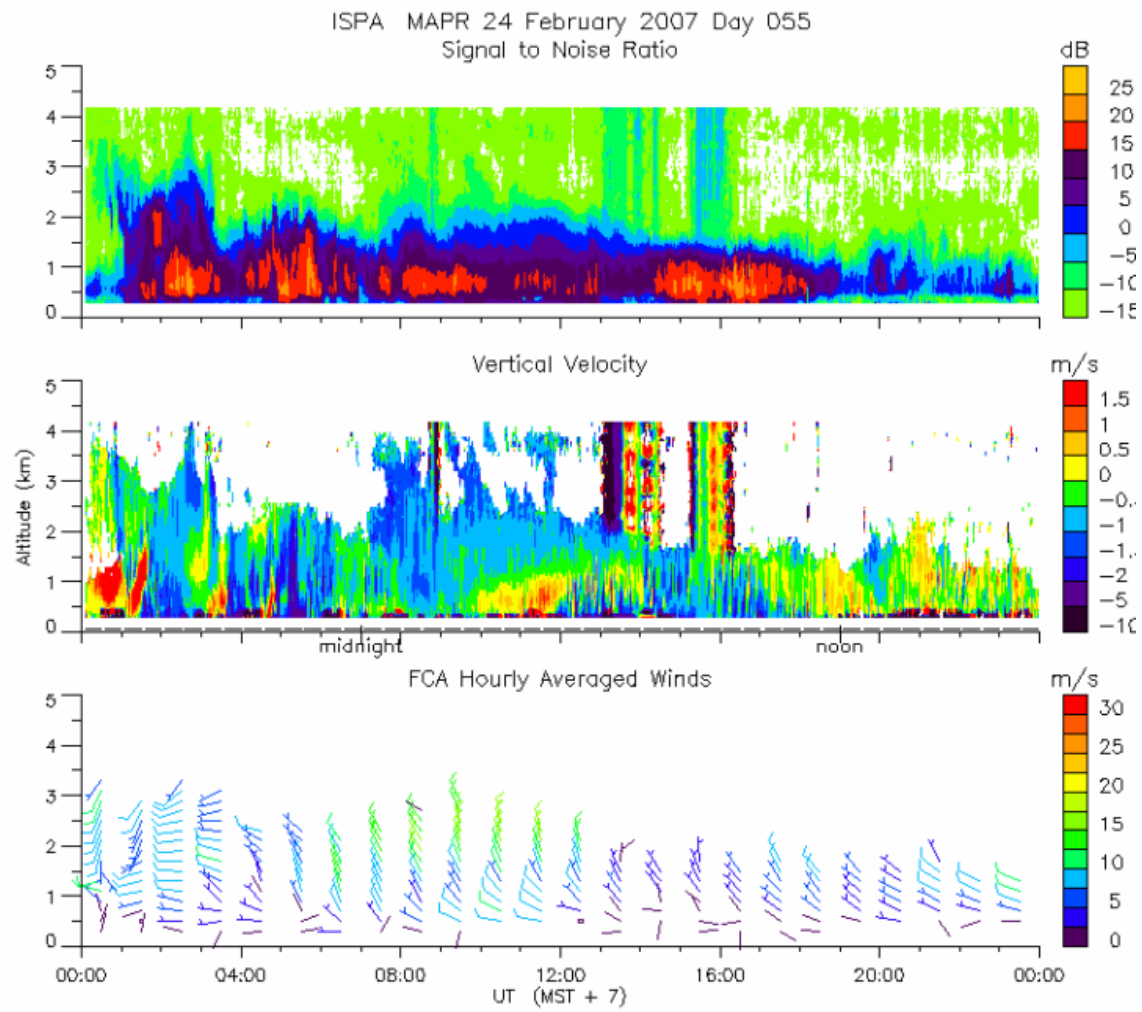
Figure 9. 24 Feb 2007 time series of NCAR MAPR precipitation, vertical velocity and wind profiles.
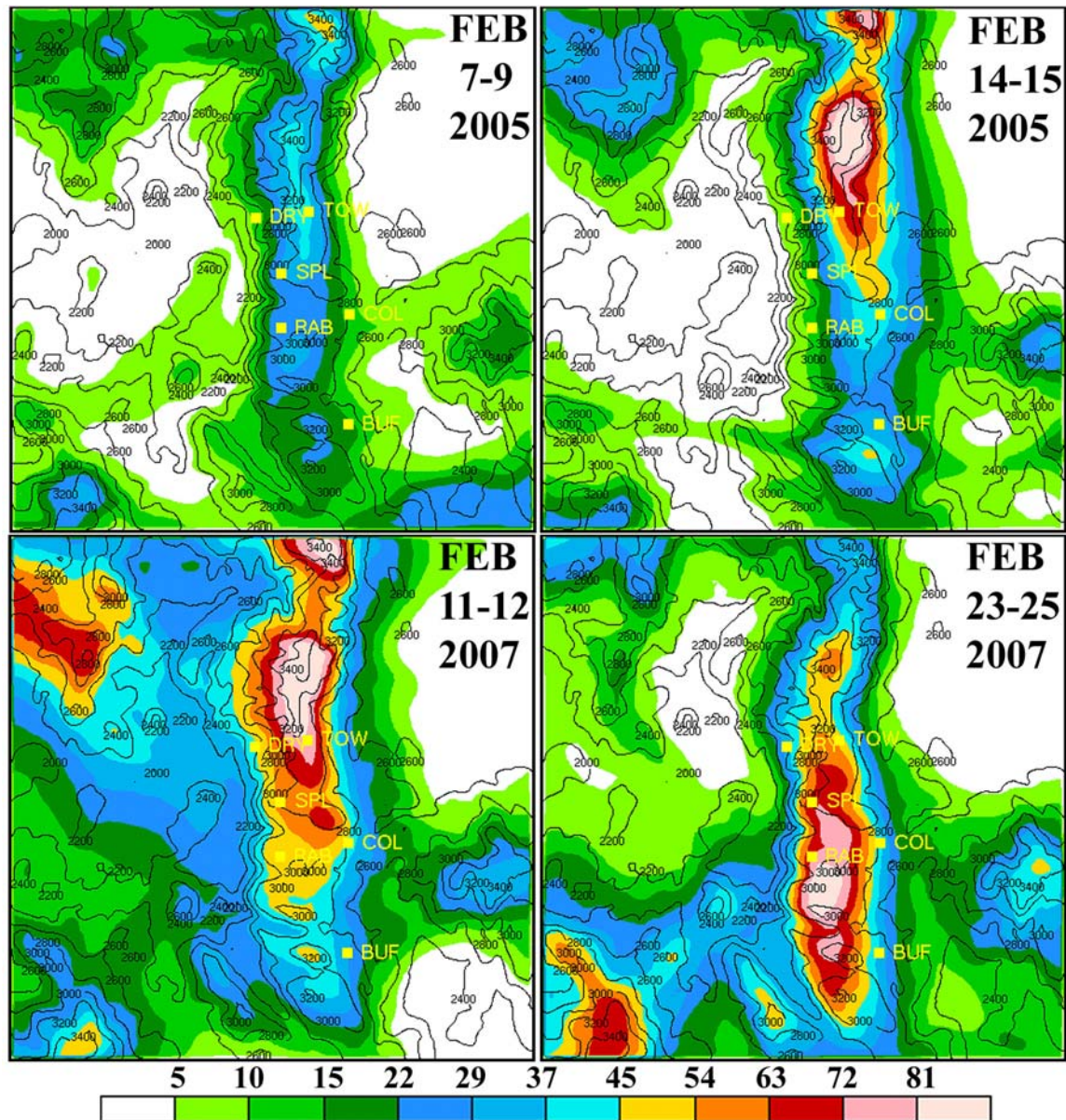
Figure 10. Total snow water equivalent (mm) accumulated during each case study. Note that the greatest snowfall always occurs along the ridge of the Park Range with a strong snowfall gradient along the sloping terrain, but the precise location of local maxima varies among cases. The locations of the following Park Range SNOTEL sites are labeled: Rabbit Ears (RAB), Columbine (COL), Tower (TOW), and Dry Lake (DRY)
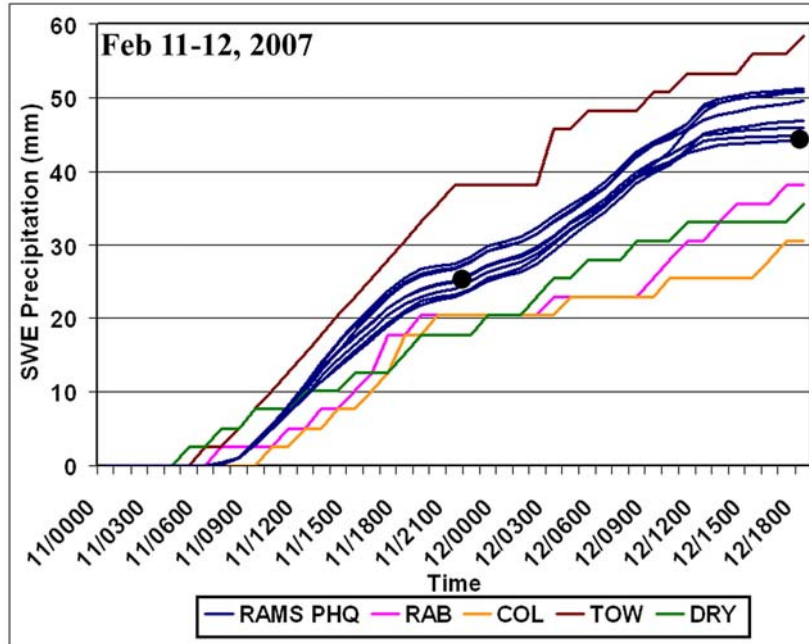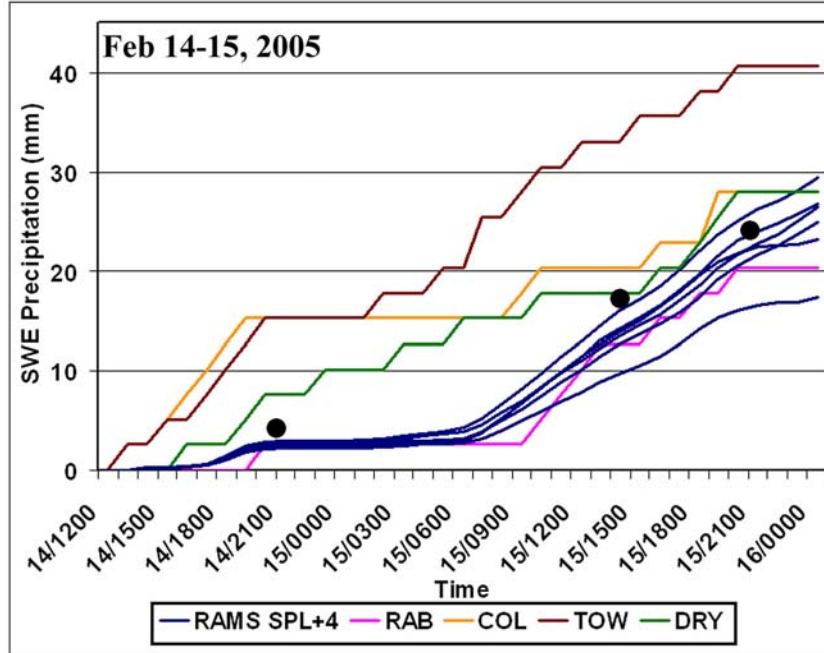
Figure 11. Time series during 11-12 February 2007 of snow water equivalent (SWE) precipitation from the ensemble of RAMS simulations (RAMS PHQ) and SNOTEL sites. The RAMS ensemble runs used CCN concentrations from $100 - 1900$/cc, GCCN concentrations from $10^{-5} - 10^{-1}$/cc, and Meyers (high) and DeMott (lower) IFN nucleation rates. The black dots depict the daily SWE measurement from the average of the Patrol Headquarters and Morningside stations nearest to SPL.
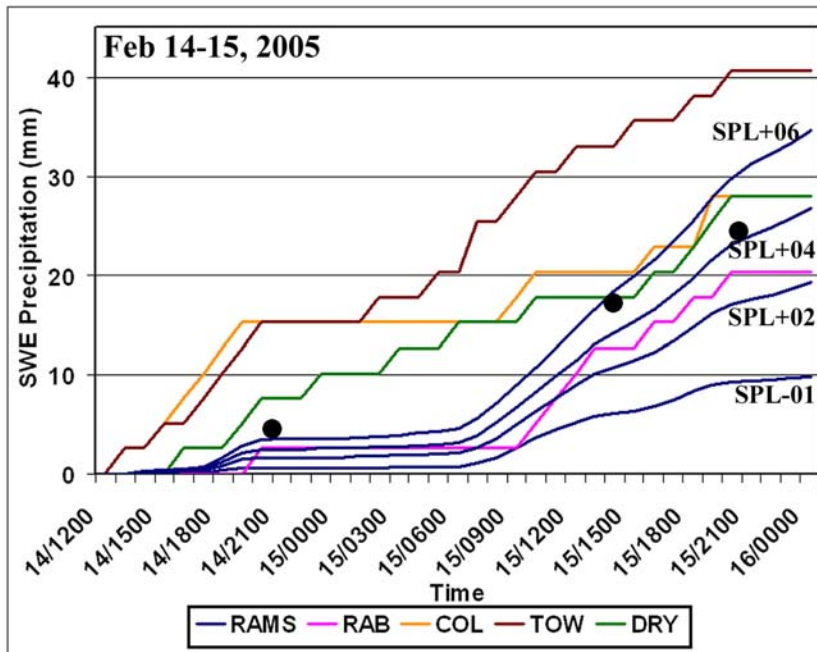
Figure 12. Time series plots of snow water equivalent from the SNOTEL sites and from RAMS model simulations from several points along a west-east transect during 14-15 February 2005. This case showed substantial slope variability in the model and in the SNOTEL sites. The black dots depict the daily SWE measurement from the Patrol Headquarters station nearest to SPL.

Figure 13. Time series during 14-15 February 2005 of snow water equivalent (SWE) precipitation from the ensemble of RAMS simulations (RAMS SPL+4) and SNOTEL sites. The RAMS ensemble runs used CCN concentrations from 100 – 1900/cc, GCCN concentrations from $10^{-5} – 10^{-1}$/cc, and Meyers IFN nucleation rates. The black dots depict the daily SWE measurement from the Patrol Headquarters station nearest to SPL.
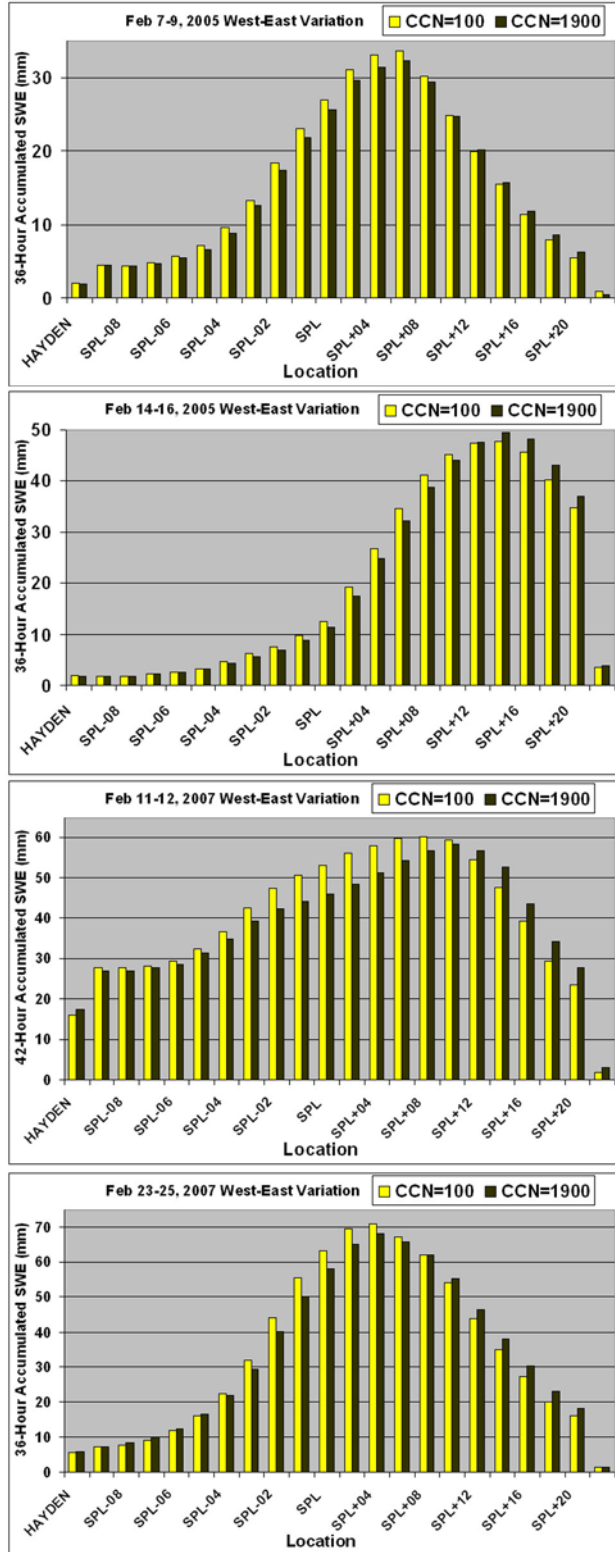
Figure 14. Total SWE (mm) accumulated during each case study along the topographic transect in Figure 2. The yellow bars indicate the simulation initialized with a "clean" CCN profile of 100 cm^{-3}, and the red bars denote the case with the "polluted" CCN profile of 1900 cm^{-3}.
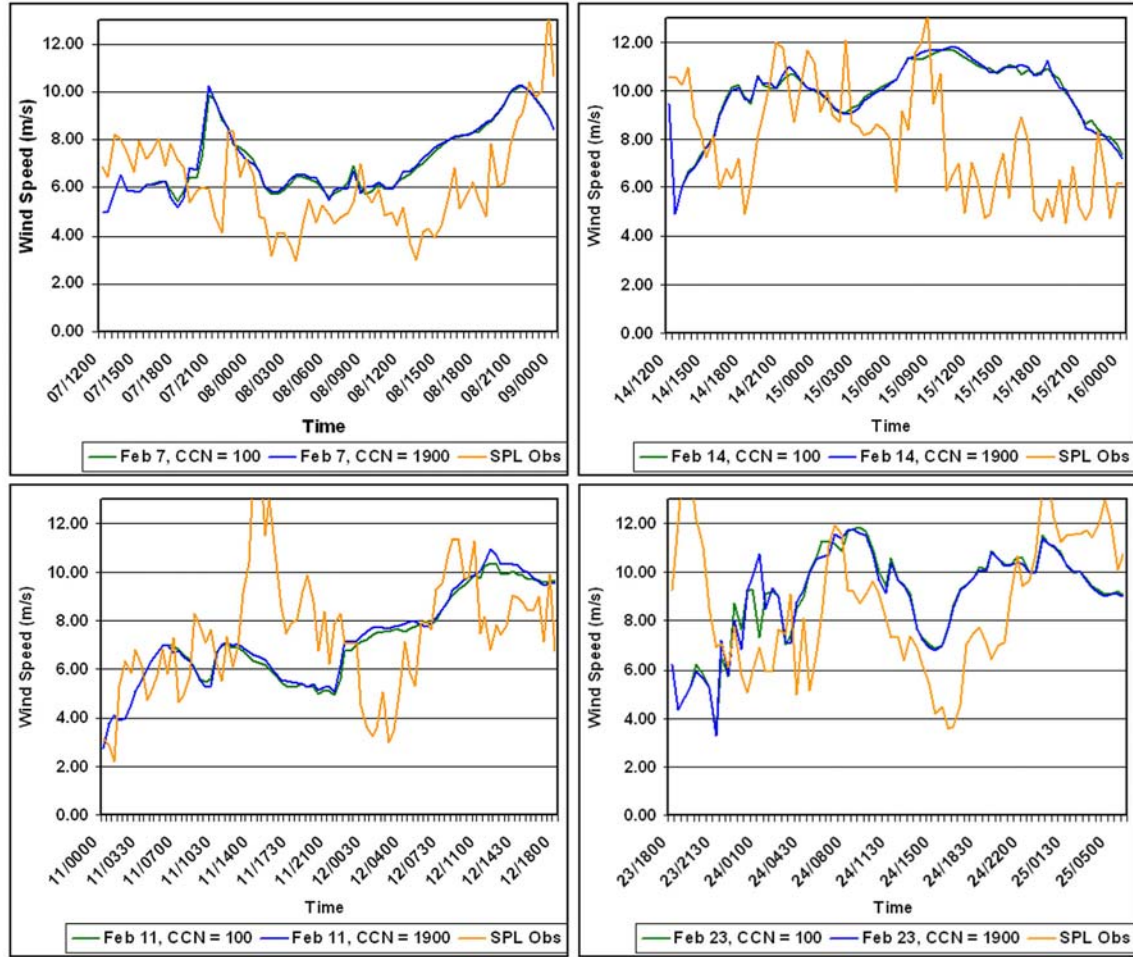
Figure 15. Time series of wind speed from observations at SPL and from the RAMS SPL grid point from selected ensemble simulations for each of the four cases. The wind speed from the RAMS simulated clean and polluted cases are plotted for comparison, and they show little difference in the winds despite the large difference in CCN concentration.
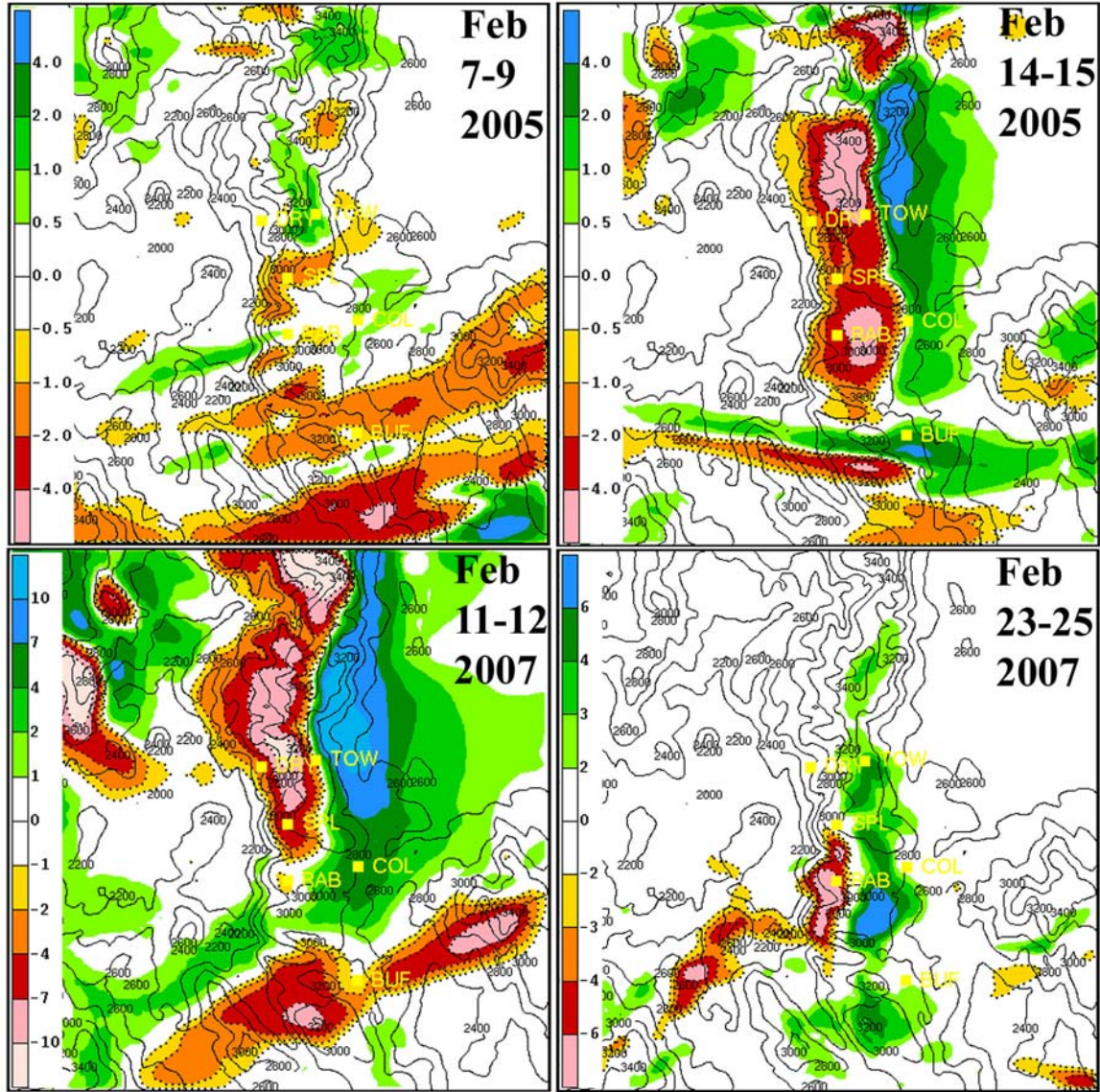
Figure 16. Total accumulated SWE difference (mm) between the simulations with the polluted and clean CCN aerosol profiles given as POLLUTED - CLEAN. Positive areas indicate an increase in SWE due to an increase in CCN and vice versa. Several local SNOTEL locations and SPL are labeled. Note that the shading scale is slightly different for each case since case lengths varied as did total precipitation.
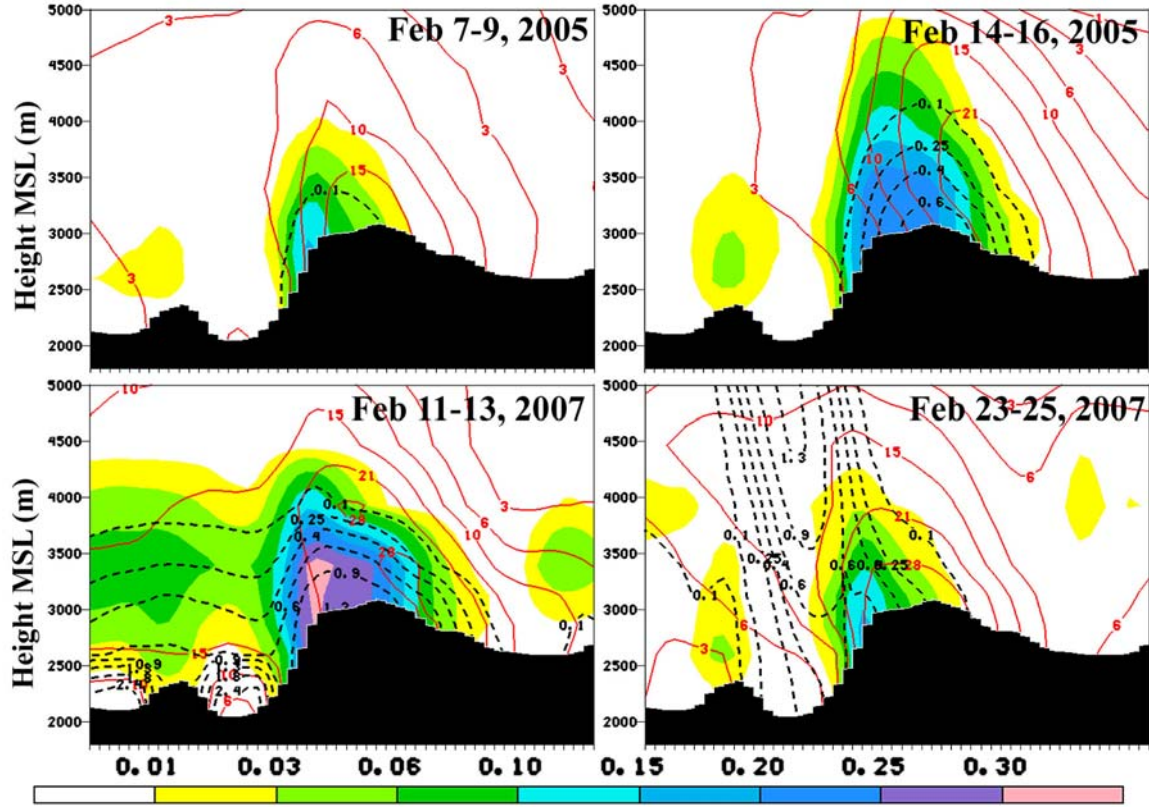
Figure 17. Cross-section of event-averaged mixing ratios of cloud water (g/kg, shaded), snow (g/kg x 100, red solid lines), and graupel (g/kg x 100, black dashed lines). These simulations ran with aerosol concentrations as follows: CCN = 100 cm^{-3}, GCCN = 10^{-5} cm^{-3}, and IFN = Meyers nucleation rates.
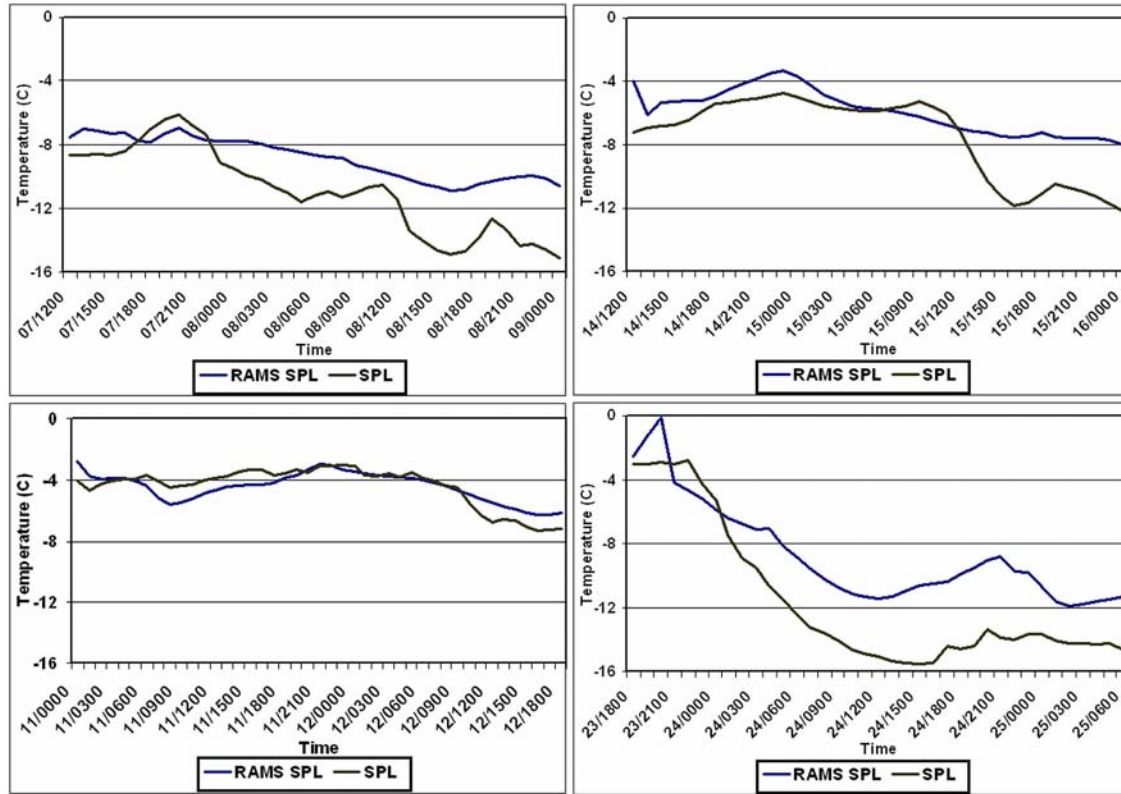
Figure 18. Time series of observed temperature from SPL and RAMS SPL grid point. The model time series come from simulations run with aerosol concentrations as follows: CCN = 100 cm^{-3}, GCCN = 10^{-5} cm^{-3}, and IFN = Meyers nucleation rates. The temperature variability with change in aerosols was unsubstantial, so only comparison to only one simulation per event is displayed.
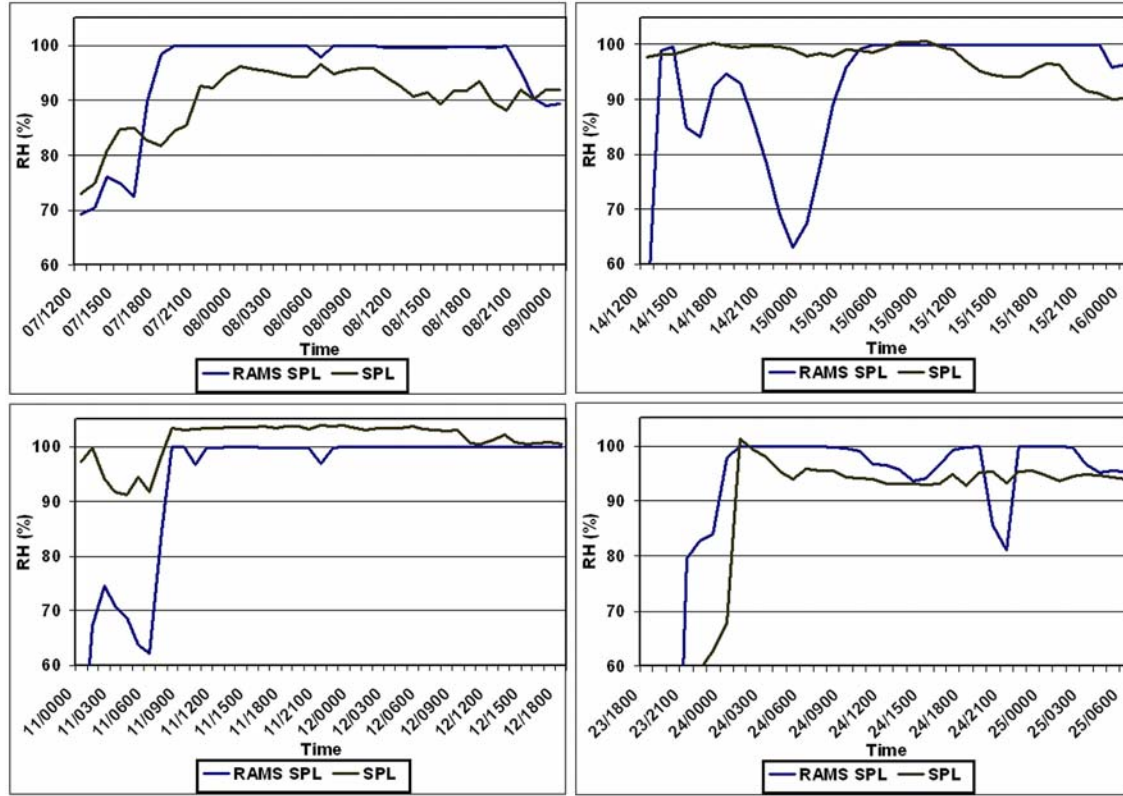
Figure 19. Time series of observed relative humidity from SPL and RAMS SPL grid point. The model time series come from simulations run with aerosol concentrations as follows: CCN = 100 cm^{-3}, GCCN = 10^{-5} cm^{-3}, and IFN = Meyers nucleation rates. The temperature variability with change in aerosols was unsubstantial, so only comparison to only one simulation per event is displayed.
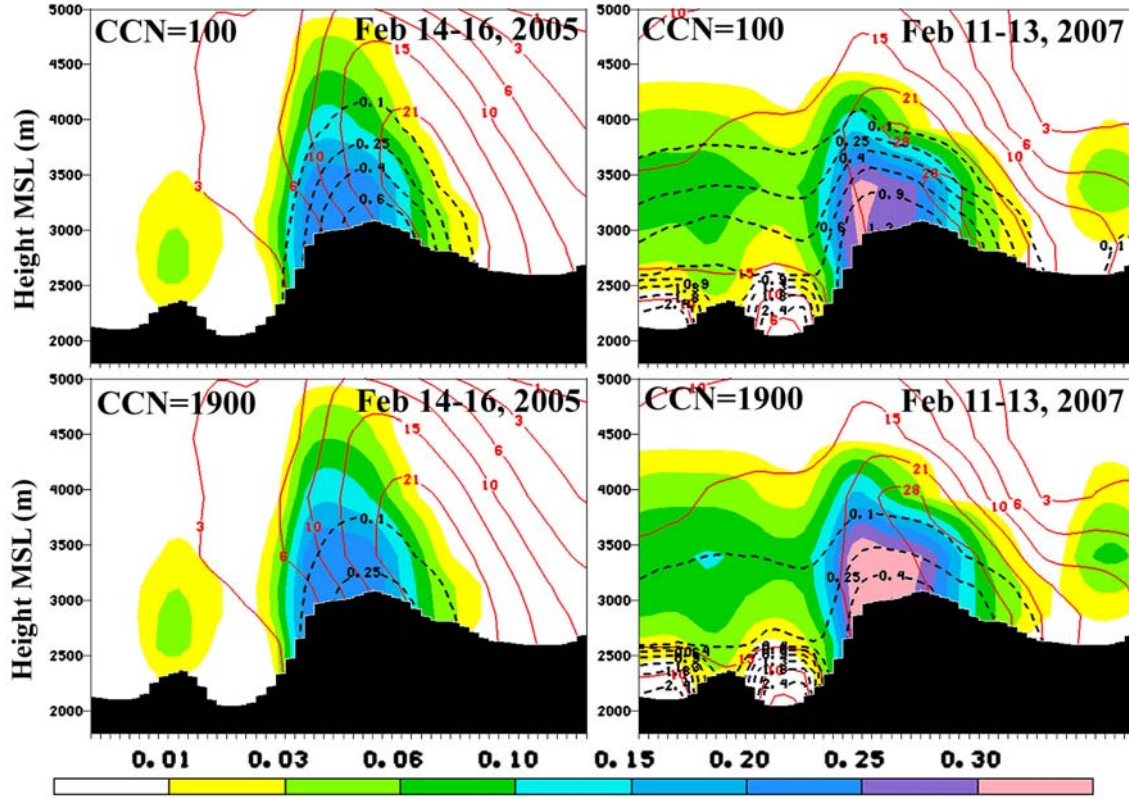
Figure 20. Cross-section of event-averaged mixing ratios of cloud water (g/kg, shaded), snow (g/kg x 100, red solid lines), and graupel (g/kg x 100, black dashed lines). These simulations ran with aerosol concentrations as follows: CCN = 100 cm^{-3}, GCCN = 10^{-5} cm^{-3}, and IFN = Meyers nucleation rates. Only 2 cases are shown with the left (right) panels from Feb 14-16, 2005 (Feb 11-12, 2007). Top (bottom) panels show simulations initialized with a clean (polluted) CCN profile.