8.5 RELATIVE IMPACTS OF OROGRAPHIC FORCING AND POLLUTION AEROSOLS ON MOUNTAIN SNOWFALL

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1. INTRODUCTION

The Park Range of Colorado receives the majority of its annual precipitation in the form of snow during the winter months. This North/South oriented mountain range is generally aligned orthogonally to the westerly mean flow that accompanies most synoptic mid-latitude cyclones over the western U.S. (see Fig. 1). In the absence of blocked flow, deep lifting of a near-surface airmass from the Steamboat Valley can be transported up and over the crest of the Park Range. This deep lifting along the slope provides for enhanced condensate production and surface snowfall that would otherwise remain limited. In addition to orographically generated condensate (snowfall), the strong cross-barrier pressure gradient and upslope wind tends to frequently produce an orographic cloud with supercooled liquid water (Rauber and Grant, 1986; Borys et al., 2000). These supercooled cloud events are frequently observed during the winter months at the Desert Research Institute's Storm Peak Lab (SPL). SPL is a high-altitude atmospheric physics lab located at the top of Mt. Werner (~3210m MSL) near Steamboat Springs, CO (Borys and Wetzel, 1997).

A seeder-feeder mechanism, involving the sedimentation of higher altitude snow crystals through the low-level orographic cloud, produces greater precipitation amounts near mountaintop due to ample riming of cloud droplets in the lowest 2km (Rauber et al., 1986a,b). This low-level riming process enhances the precipitation efficiency, such that, the amount of rime has been shown to comprise from 20% - 50% of the final snow mass that reaches the surface (Borys et al., 2003). Enhanced riming will increase the mass of snow crystals as well as the fall speed; this increases the likelihood of higher snow deposits along windward slopes (Hindman, 1986). Slower falling, unrimed snow crystals are more likely to fall on the leeward slopes where subsidence leads to evaporation, a reduction in total surface snowfall, and disappearance of the "feeder" cloud (Rauber et al., 1986a,b).

While orography and riming may result in locally enhanced snowfall, intrusions of high concentrations of pollution aerosols, in the form of sulfate-based cloud condensation nuclei (CCN), can modify the droplet spectra in the supercooled orographic cloud. Changes in the droplet size distributions will impact the snow riming efficiency (Hindman, 1994). Borys et al. (2000) found that increased aerosol concentrations suppress formation of larger cloud droplets and reduce riming of cloud droplets by ice hydrometeors.

This study examines the relative impacts of orography, riming, and pollution aerosols on total snowfall and snowfall distributions near the Park Range of Colorado. This is accomplished with use of a mesoscale model to produce high resolution simulations of winter orographic snowfall events.

2. MODEL DESCRIPTION

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 CCN number concentration. The non-hydrostatic, compressible version of RAMS is configured on an Arakawa-C grid and sigma-z terrain-following coordinate system (Cotton et al., 2003). For these simulations, the model uses two-way nesting with a nested 4-grid arrangement centered over 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 grid spacing. The model uses vertical grid stretching with a stretch ratio of 1.12 and a maximum vertical grid spacing of 750m.

The RAMS model contains a highly sophisticated, state-of-the-art microphysics package that predicts on two-moments of the hydrometeor distributions (mixing ratio and number concentration) for rain, pristine ice, snow, aggregates, graupel, and hail (Cotton et al. 2003). Saleeby and Cotton (2004) extended the two-moment approach to the cloud droplet distribution via a parameterization for the formation of cloud droplets from activation of CCN within a lifted parcel. The Lagrangian parcel model of Heymsfield and Sabin (1989), was utilized to determine the percent of user-specified CCN that would activate and grow by condensation into cloud droplets for a given ambient temperature and vertical velocity. 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.

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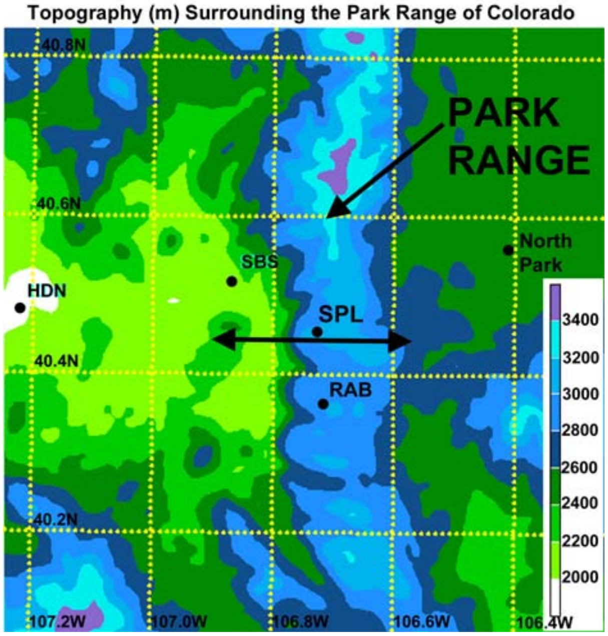

Figure 1. RAMS Grid-4 with grid spacing of 750m. Topography is overlaid (m). Locations of Hayden (HDN), Steamboat Springs (SBS), Storm Peak Lab (SPL), Rabbit Ears Pass (RAB), and North Park are labeled for reference. The bold-horizontal line depicts the cross-section range in figure 2.

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 CCN concentration was initialized horizontally homogeneous with a vertical profile that decreases linearly with height up to 4km AGL. Initial surface concentrations were varied from 100 – 1900 cm^{-3}; the minimum concentration allowed at any location was 100 cm^{-3}. 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 36hr simulations were conducted for two snowfall cases beginning 1200 UTC on Feb 7 and Feb 14 of 2005. The 32km North American Regional Reanalysis was used for model initialization and nudging of the lateral boundaries.

3. OROGRAPHICALLY VARIED PRECIPITATION

All analyses discussed herein are results from the high resolution grid with 750m grid spacing. This fine resolution provides numerous grid point calculations along the sloping terrain to the west and east of SPL. The steepest terrain adjacent to SPL is the western slope that descends to the valley of the Steamboat Springs ski resort. The model contains 10 grid points at various elevations between SPL and the base of the ski resort. This allows for a high resolution look at the impact of orography on snowfall amounts as well as the

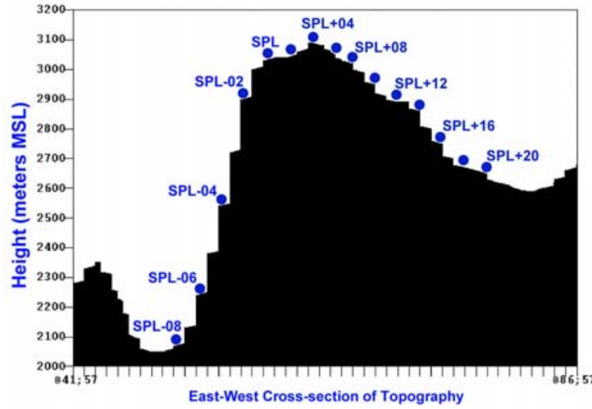

Figure 2. West to east model topographic cross-section centered roughly on SPL. Blue dots depict location of horizontal grid points, such that "SPL+04" is 4 model grid points east of SPL. Cross-section location is shown by the horizontal, bold, arrow-tipped line in figure 1.

influence of CCN concentration at various points along the terrain. Figure 2 provides a west to east cross-section of topography, centered on SPL, with reference locations labeled on the figure that will be pointed to in this paper. There are four key inter-related factors in these simulations that combine to impact the total precipitation in a manner that would otherwise be inconsequential over flat terrain.

a. Park Range Topography

The 1st factor is the existence of the Park Range topography. This is the primary mechanism for generation of enhanced condensate and surface snowfall. This lengthy barrier leads to enhanced upslope flow, stronger updrafts on the windward slope, and greater localized precipitation efficiency. This mountain range is the catalyst for the other precipitation modification factors. Figure 3 displays the accumulated precipitation along the west to east slope of the Park Range from the Feb 7th and 14th cases. The grid point labels on figure 3 are shown on the topographic cross-section in figure 2. The impact of the mountain is quite apparent with up to a 10 fold increase in precipitation between upstream, flatland areas and the maximum orographic impact.

b. Hydrometeor Advection

The 2nd factor is horizontal advection of falling precipitation. For horizontal flow to create an optimized orographic influence, the ambient Froude number must allow for cross-barrier flow and there must be enough momentum to generate enhanced vertical motion from the horizontal winds. Beyond a necessary minimum in horizontal flow for the generation of orographic precipitation, the strength of the mean wind will impact the spatial distribution of the orographic snowfall. Stronger horizontal advection will tend to displace falling hydrometeors further downstream from the initial point of updraft condensation and ice crystal formation. For winter cloud seeding enthusiasts at ski resorts, on-site ground based seeding may enhance condensate production near a resort and then transport snowfall

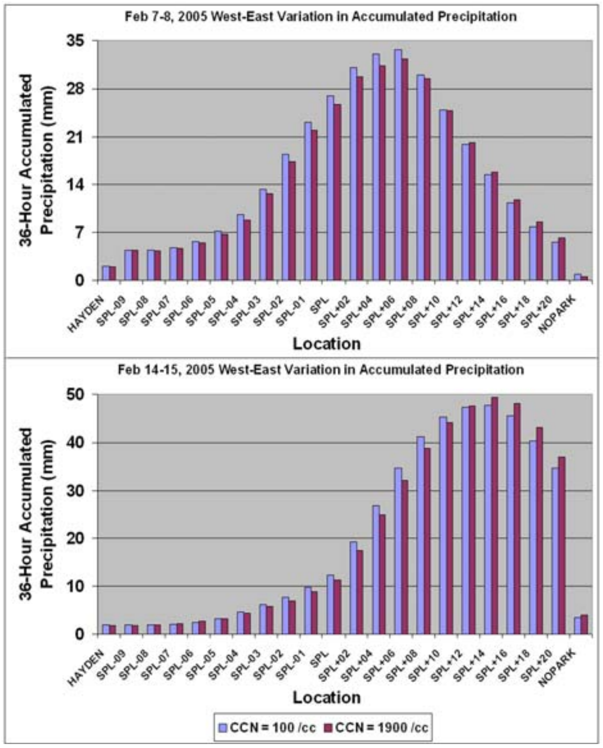

Figure 3. Accumulated precipitation for locations pointed to in figures 1 and 2. Graph also displays difference in accumulation between the cleanest (max CCN = 100 cm^{-3}) and most polluted (max CCN = 1900 cm^{-3}) case.

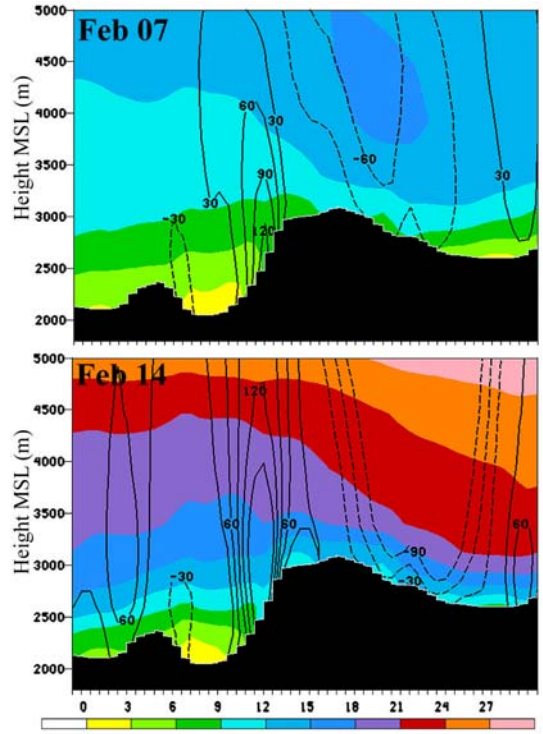

Figure 4. West to east model cross-section of time averaged horizontal wind (shaded, m/s) and vertical wind (contoured, cm/s) from 7-8 Feb (top) and 14-15 Feb (bottom). These simulations were initialized with CCN concentration of 100/cc.

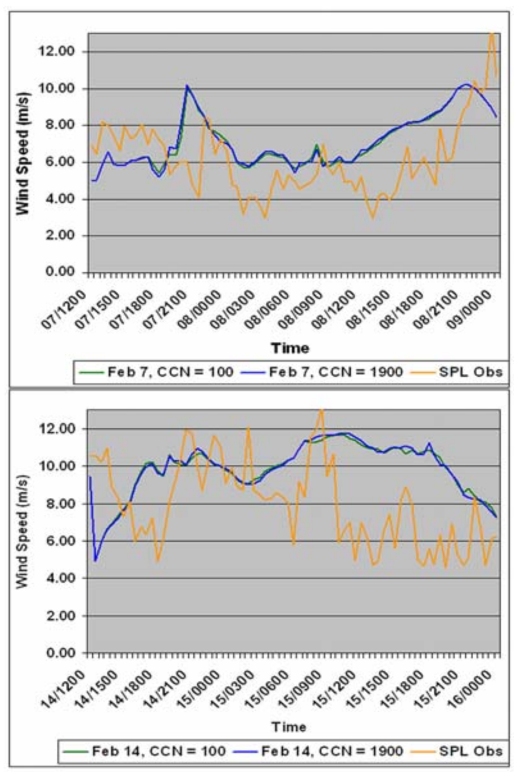

Figure 5. Time series of RAMS wind speed at the grid point closest to SPL and the SPL observations (m/s) from 7-8 Feb (top) and 14-15 Feb (bottom).

from the seeded cloud to off site areas downstream. This would be a costly mistake with no benefit. From figure 3, it can be seen that the maximum snowfall does not occur directly above the topographic maximum. On Feb 14th this is especially apparent, with the maximum snow deposited nearly 8km downstream from the summit. To compare the potential difference in advection between these cases we examine the averaged winds in figure 4. The horizontal and vertical winds are substantially stronger in the 14 Feb case. As such, we see a greater downstream accumulation of snowfall. There is essentially a spatial lag between the sloping terrain and hydrometeor surface deposition that depends on ambient horizontal wind speed. It is also important to note that the stronger dynamics in the 14 Feb event lead to greater convergence and upward motion on the windward slope and greater overall snowfall totals. Further, the leeward subsidence is also greater; thus, the downstream advection will have its limits due to stronger evaporation on the lee slope. Time series of the winds, in figure 5, from SPL observations and the RAMS closest grid point to SPL also show generally stronger winds in the 14 Feb case, which, leads to greater hydrometeor transport and larger accumulations on the leeward slope.

c. Supercooled orographic cloud

A 3rd factor influencing the accumulated snowfall and snow water equivalent (SWE) is the potential riming of snow falling through supercooled cloud water. The summit of Mt. Werner is frequently enshrouded in a supercooled cloud from December through March (Rauber et al., 1986a,b; Borys et al. 2000). The formation of a supercooled cloud requires deep, sustained orographic lifting that maintains water saturation. Further, there cannot be an overabundance of in situ ice, which may create an overactive Bergeron process and deplete the liquid droplets. A delicate balance must be maintained to allow liquid water to exist and prevent the cloud from glaciating.

Once a stable cloud has formed, snow crystals falling through this cloud will accrete a portion of the cloud water and deposit this extra water mass at the surface. The degree of riming depends largely upon the amount of cloud water and the mean diameter of the droplet spectra. Low LWC or small droplets will lead to very light riming, while high LWC and larger diameter droplets will lead to heavy riming. Heavily rimed crystals have greater fall speeds and are less susceptible to downstream advection. Figure 6 displays the simulated orographic cloud at the times of maximum liquid water content from the two cases. The 14-15 Feb event, with the stronger dynamics, has an orographic cloud of greater depth and horizontal extent. It also exhibits greater snow mixing ratio further downwind of the summit, with riming more likely on the lee slope.

d. Pollution Aerosols

Lastly, the concentration of sulfate-based pollution aerosols (CCN) will affect the degree of riming by altering the droplet spectra. High concentrations of CCN lead to high concentrations of small droplets, whereas, low concentrations of CCN result in fewer, larger droplets. Smaller droplets have much smaller collection efficiencies, and are less likely to be rimed and contribute to the total surface water. From figure 3, we see that the simulations with the higher CCN concentration resulted in suppressed SWE on the windward slopes and increased SWE on the leeward slopes. There is not simply a reduction in precipitation everywhere due to the pollution, but rather a re-distribution due to enhanced downstream advection of the more lightly rimed, slower falling crystals in the polluted cases. When comparing the two case days, it is also interesting that the pollution impact is greatest under the day with stronger winds and upslope flow. Part of this is certainly attributed to the larger orographic cloud on 14 Feb. The greater lee slope precipitation on the 14th in the polluted case is mostly likely enhanced due to stronger advection.

Variations in CCN concentration also impact the form of precipitation that reaches the surface. From figure 6, both case days exhibit the presence of graupel only when the CCN concentration is low. In RAMS, graupel is mixed-phase and forms only under conditions of heavy riming; in such high altitude wintertime cases, this tends to only occur when CCN and droplet concentrations are at a minimum and collection efficiencies are high. While graupel is present on both days under low CCN concentrations, it is distributed more downstream on 14 Feb due to stronger advection.

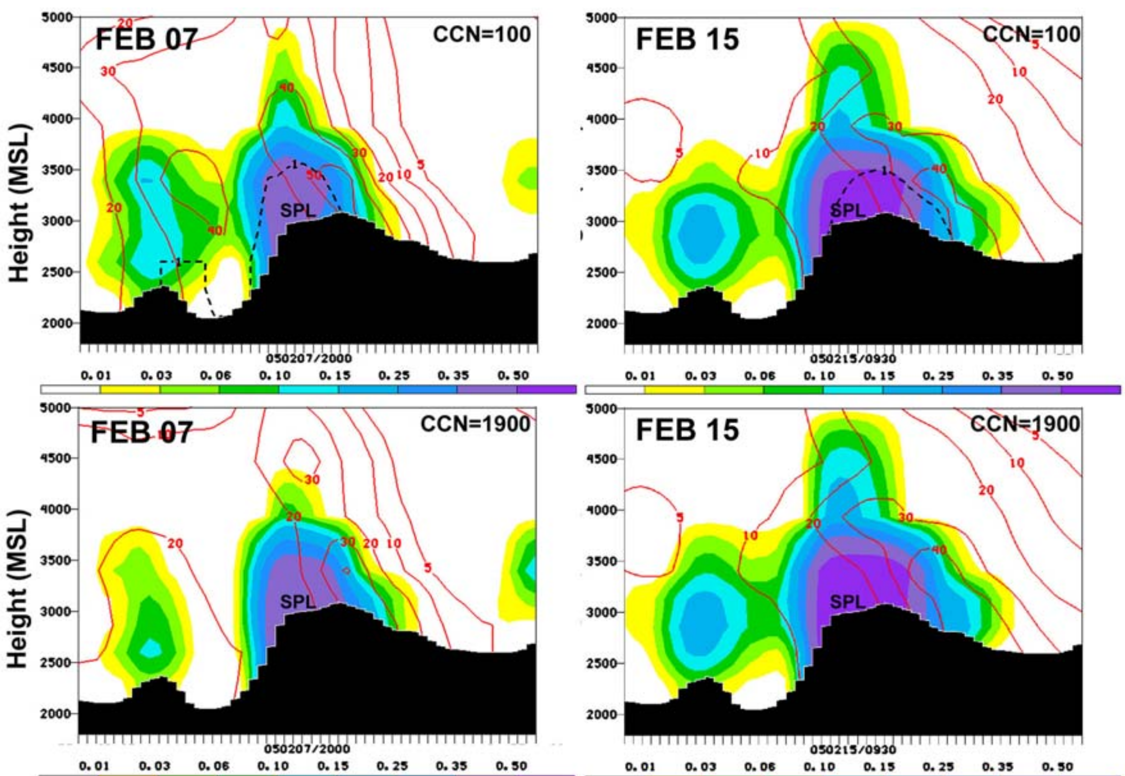

Figure 6. Cross-section of mixing ratio for cloud water (g kg^{-1}, shaded), snow (g kg^{-1} x 100, solid red lines), and graupel (g kg^{-1} x 100, black dashed lines). Top (bottom) panels are from the clean (polluted) simulation. SPL location is noted, and each tick mark is 750m. The chosen times contain the maximum cloud liquid water content.

4. CONCLUSIONS

The CSU-RAMS model has been utilized in the current study to investigate the relative impacts of local storm dynamics and pollution aerosols on orographically enhanced wintertime precipitation. The nested, fine resolution grid with 750m grid spacing was focused over the north-south aligned Park Range of Colorado. RAMS was chosen for this study because of its parameterization for the activation of aerosols and nucleation of cloud droplets (Saleeby and Cotton, 2004), as well as its newly implemented binned scheme for simulating the riming growth process of frozen hydrometeors (Saleeby and Cotton, 2007).

In this study, a set of 36 hour simulations were run for two snowfall events beginning 1200 UTC on 7 Feb and 14 Feb. RAMS was run for the duration of these cases with varying profiles of maximum CCN concentration from 100 to 1900 cm^{-3}. The extremes of this range essentially represent a clean versus polluted type of environment.

Four factors were discussed that influence the total precipitation over the Park Range during winter months. The primary component is the presence of steep topography that enhances precipitation formation due to the upslope component of flow impinging upon the barrier. The second factor is the strength of the flow, which impacts the degree of convergence along the slope and the horizontal transport of topographically generated snowfall. The strength of the horizontal wind impacts the spatial distribution of orographic snowfall due to a blowover effect. Stronger winds displace more snowfall to the lee slope in the simulated cases. Thirdly, the development of a supercooled orographic cloud that enshrouds the mountain crest acts as a feeder cloud for collection of droplets by snow crystals falling from above. This enhances the total surface SWE. A large, efficiently rimed orographic cloud can substantially increase the total precipitation.

Lastly, the intrusion of pollution aerosols (CCN) can modify the orographic cloud and impact the riming efficiency. The precipitation along the upwind slope was reduced in the highly polluted cases. However, the leeward slope experienced an increase in precipitation, due to blow-over from the windward side of the mountain. The droplet concentration and size impacts the degree of riming, and, thus, the snow crystal sizes. In the polluted case, the droplets are smaller and have lower riming efficiencies. This results in smaller snow crystals with slower fall speeds that are transported further downwind before depositing at the surface.

From the winter cases simulated thus far, we have seen that a large increase in CCN concentration only modifies total precipitation up to around 10% when cold cloud processes dominate. This impact is much less than the dynamical impact of the orography and strength of the impinging flow. From case to case, the variation in the dynamics creates greater variation than the degree of pollution. Of the influences discussed here, however, the amount of pollution is the only one over which we have any control.

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