J44.2 Evidence of Microphysical Buffering of CCN Impacts on Wintertime Orographic clouds

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1. Introduction

There is increasing evidence that cloud responses to increasing concentrations of cloud nucleating aerosols is by no means simple and linear. Stevens and Feingold (2009) introduced the term “buffering” to represent those processes whereby CCN pollution can lead to no change or little change in precipitation owing to complex microphysical and dynamical processes that can alter the seemingly simple response of clouds to aerosols. The purpose of this paper is to show that even in simple cloud systems where dynamical responses are quite small, microphysical buffering of aerosol forcing can lead to little change in precipitation or even an increase in precipitation in opposition to the basic hypothesis that increased aerosol concentrations will decrease precipitation. Here we use two examples, one being a cold-based continental wintertime orographic cloud system in which there is little evidence of drizzle processes. The second being a relatively warm-based wintertime orographic cloud system in which drizzle processes are quite active.

2. The cold-based continental wintertime orographic cloud system

Borys et al., 2000; Borys et al., 2003) found a correlation between sulfate concentration in collected cloud water and cloud droplet number concentration and an inverse correlation between sulfate amount and accumulated snowfall in the Rocky Mountains. Pollution increases the number concentration of cloud condensation nuclei (CCN) and therefore cloud drops; this leads to the formation of smaller cloud drops and less efficient riming. A reduction in riming results in smaller, pristine ice crystals that have smaller fall velocities and less surface precipitation accumulation. Figure 1 illustrated the difference ice crystal properties for clean and polluted conditions.

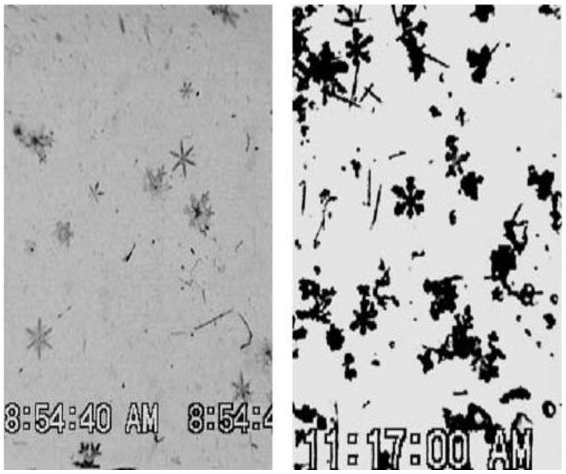

Figure 1 Light riming of ice crystals in clouds affected by pollution (left) compared to heavier riming in non-polluted clouds (right) (Borys et al. 2003).

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In a series of modeling papers, Saleeby et al. (2009, 2011, 2012) showed that while aerosol pollution lead to the formation of smaller, more numerous droplets and reduced riming, overall total precipitation was reduced only a small amount. Reduced riming lowered snow water equivalent precipitation amounts on the windward side of mountain barriers and increased it on the lee slopes. This so-called “spillover effect” led to a downstream shift of precipitation from the Colorado River Basin to the Atlantic watershed. They also showed that this effect was only important for relatively wet storms where riming is important. Low supercooled liquid water content storms are less influenced by aerosol pollution. This is best illustrated in Figure 2 which shows the differences between precipitation amounts for a 60-day period for four different years. The “spill-over” is quite evident as well as the interannual variability of the simulated response to CCN concentration variability. The maximum net change in domain total precipitated water volume resulting from an increase in aerosol concentration from clean to polluted occurred in 2005, and was a reduction of only -1.48%. The total spillover loss was -2.96% and total spillover gain was 1.48%. The Colorado river basin is overall the big loser with as much as 522,000 acre-ft lost in a 60 day period due to the “spillover effect” in 2005.

Why is total water changed so little? Saleeby et al(2012) developed a conceptual model that depicts the primary physical processes involved in orographic precipitation formation and their predominant locations. This figure illustrated that the main microphysical growth processes within these orgographic clouds are:

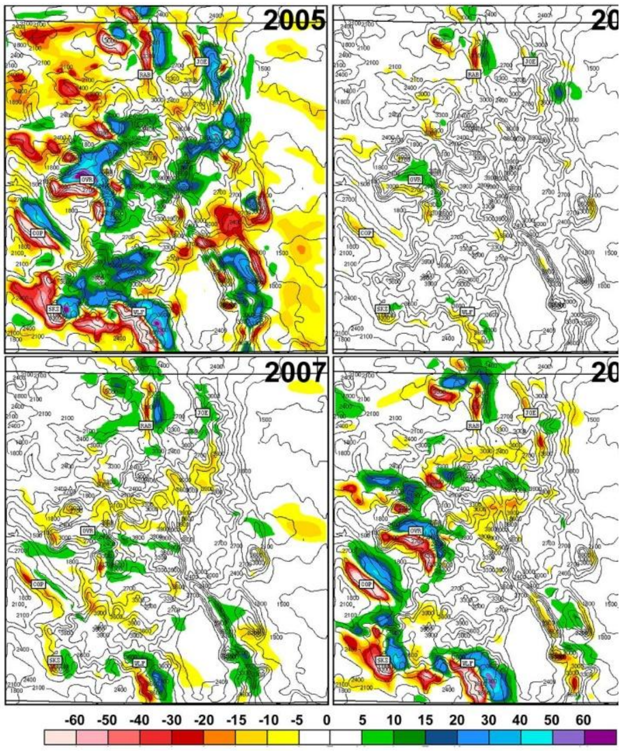

Figure 2. Simulations of Aerosol Impact on 60-Day Cumulative Difference in SWE(From Saleeby et al, 2011).

1. Cloud droplet vapor deposition is concentrated on the windward slope and western side of the topographic ridgeline with a maximum near the top of the windward slope.

2. Cloud droplet riming is maximized over the ridge, just downwind of the cloud vapor growth maximum, and typically within 500m of the surface.

3. Cloud droplet evaporation is primarily located along the ridgetop and lee slope. It overlaps the lee slope riming zone and often extends slightly further down the lee slope than the riming zone.

4. Ice vapor deposition is typically maximized approximately 1-1.5 km above the windward slope, extending downwind

above the ridgetop and above or overlapping the ridgetop cloud droplet riming zone.

5. Ice sublimation is maximized further down the lee slope into the subsidence zone than droplet evaporation since the environment is less sub-saturated with respect to ice than water.

When cloud droplet nucleating aerosols are increased in this environment the microphysical growth processes mentioned above are modified in the following manner:

a. Cloud droplet vapor deposition growth is increased on the windward slope.

b. Cloud droplet riming growth is decreased everywhere riming is occurring.

c. Cloud droplet evaporation is increased on the leeward slope and ridgetop.

d. Ice species vapor deposition growth increases on the windward size of the lee subsidence zone and ice sublimation decreases along the lee slope in the subsidence region.

e. The Wegener-Bergeron-Findeisen (WBF) ice growth process is enhanced along the ridgetop and also possibly along the windward and lee slopes.

f. Within snowfall spillover zones, the increase in the WBF ice growth process nearly offsets the reduced riming growth, thus, contributing to a spillover effect without a major reduction in total domain surface snowfall.

Thus we see that other things being the same, more numerous small cloud droplets evaporate more quickly than fewer bigger droplets(owing to larger surface area). As a result the WBF process is enhanced in the polluted clouds thereby buffering the riming-induced reduction in precipitation efficiency. In summary the WBF process acts to buffer the impact of enhanced CCN concentrations on total precipitation.

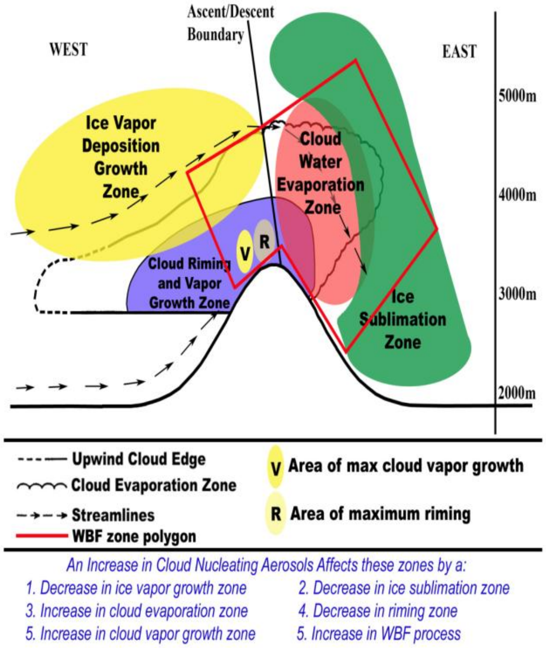

Figure 3. Conceptual model showing a vertical cross-section of the maxima in cloud and ice particle microphysical growth processes based on features common to each event simulated in this study. The impact of aerosols on these processes is summarized beneath the cross-section (Adapted from Borys et al. 2003 and Rauber 1981). Note that variations in aerosol concentration tend to modify the expanse of the processes and precise location of the maxima.(From Saleeby et al.,2012).

3. Wintertime orographic clouds where drizzle precipitation is active

Lynn et al. (2007) suggested that increased aerosol concentrations can actually increase the liquid water content (LWC) available for accretion within the supercooled region of the orographic cloud by shutting off collision-coalescence at lower elevations within the cloud. Muhlbauer et al. (2010) suggest that the sensitivity of orographic snow to CCN was highly variable on a case-to-case basis. We argue that because wintertime orographic precipitation in Colorado is almost entirely derived from cold precipitation processes, these cloud responses to increased CCN is less of a factor within that region.

Thus we explore the hypothesis that in drizzling wintertime orographic clouds increased CCN concentrations can suppress drizzle, increase cloud LWC, and thereby buffer the aerosol suppression effect and may even lead to enhanced precipitation.

We explore this effect in the Sierra Nevada Mountains of Southern California, where maritime air-masses, rich in moisture,

can generate clouds at altitudes low enough for warm-rain processes to occur. We performed a series of two-dimensional simulations with RAMS to evaluate the hypothesis. In all, 49 numerical simulations were performed along the transect across the Sierra Nevada shown in Figure 4. This series of idealized two-dimensional numerical experiments covered a 48-hour period centered on 16 February 2011. Horizontal grid spacing of 500m and vertical grid spacing of 50m near the surface, stretched to a maximum of 500m aloft was used. This case eventually ingested pollution aerosols into a highly supercooled and more pristine cloud layer riding above the boundary layer (Paul DeMott, personal communication). Potential CCN concentrations were varied from 300 to 1500 cm-3. All simulations used a uniform wind speed normal to the barrier of 15m/s, constant with height to 10km, and increases linearly above 10km to 40m/s at the model top.

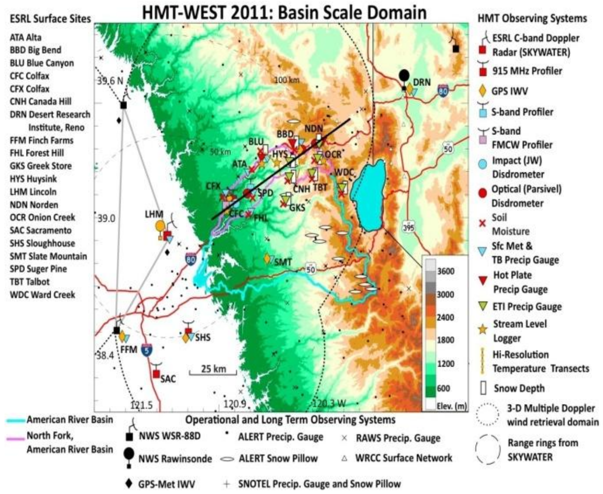

Figure4. The solid black line approximately represents the location of the 2-D domain used from the numerical experiments.

For this numerical study, we used the bin-emulating bulk microphysical model (Saleeby and Cotton, 2004) that predicts both mass mixing ratio and number concentrations of all hydrometeor species (cloud droplets, drizzle drops, rain, pristine ice, aggregates, snow, graupel, and hail). This microphysical module, among other features, considers the explicit nucleation of cloud droplets based on the activation of potential CCN, the consideration of a large cloud droplet mode that in combination with the traditional single mode of cloud droplets, allows a more accurate representation of the bimodal distribution of cloud droplets. In addition, riming is among the many collisional processes using a bin-emulating approach (Saleeby and Cotton, 2008).

Soundings were derived from the NARR dataset representative of the pre-storm environment and the environmental changes during a 48-hour period starting January 15 12Z. These soundings were nudged at the east boundary of our 2-D domain.

For the 49 numerical experiments using these soundings, cloud base temperature was varied (by varying low-level moisture) systematically such that the depth of the cloud layer below the melting level increases. Increases in vapor content up to 20% were considered. In addition, for each cloud base temperature regime, potential CCN concentrations were varied from 300 to 1500 cm^{-3}. Figure 5 gives a schematic representation of this experimental design.

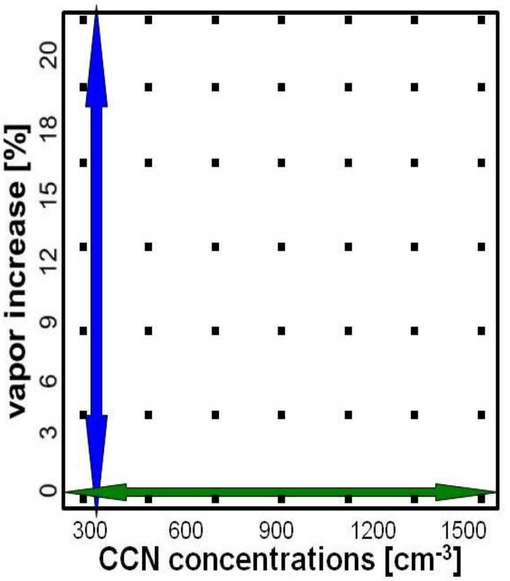

Figure 5. Sensitivity experiments. Each point represents an individual simulation. The x- axis varies potential CCN concentrations; the blue arrow denotes runs for the cleanest air mass. The y-axis enhances vapor with respect to NARR soundings; the green arrow denotes runs that ingests the soundings.

4. Results

The total mass of snow precipitation accumulated over the transect and during the entire simulation period was computed for all 49 runs. In order to focus on the aerosol effect, Fig 6 shows the percent increase in the integral mass of precipitation for the various humidity levels, relative to that of the corresponding cleanest run (potential CCN = 250 cm-3). CCN effects on the integral mass of precipitation tend to be negative although rather small (lower than 1% in module) for the lowest humidity levels close to those of the soundings. At higher vapor contents, this tendency begins to revert. For the highest considered humidity levels, increasing potential CCN concentrations results in a monotonic snow precipitation enhancement up to 4%.

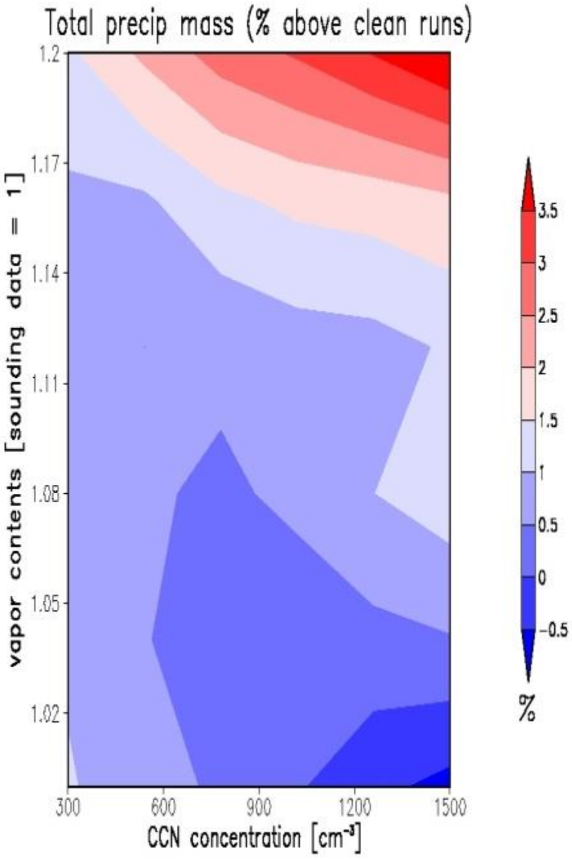

Figure6. Change in the integral mass of precipitation. Percent increases are relative to the corresponding clean cases.

Figure 7 illustrated changes in the time-averaged integral mass of supercooled liquid water (SCLW) for each simulation. This figure is analogous to Fig 6 as it shows the percent increase in the quantity for the various humidity levels, relative to that of the corresponding cleanest run. For the highest humidity levels, increasing potential CCN concentrations results in an important response of the averaged SCLW mass. The later response is linked to increases in integral mass of precipitation (Fig 6). However, for potential CCN concentrations below 900cm^{3}, the SCLW mass shows a response similar to cases characterized by lower vapor contents.

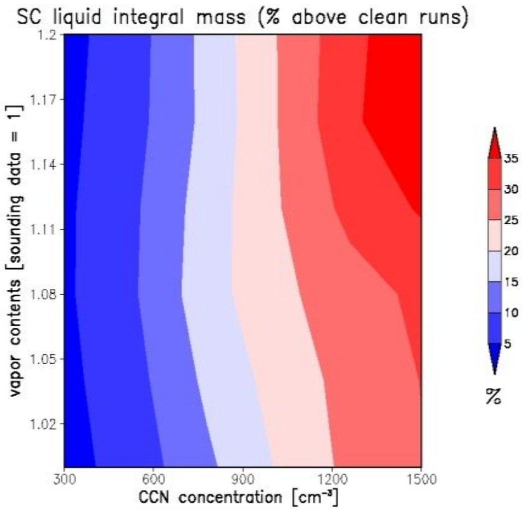

Figure 7. Change in the average integral mass of supercooled liquid water. Percent increases are relative to the corresponding clean cases.

The integral mass of liquid precipitation accumulated during the entire simulation period for each experiment is compared in figure 8. Shaded areas represent liquid water masses of precipitation corresponding to each run and normalized by the peak simulated value. If we compare this figure to Fig. 6, it can be seen that the monotonic response of snow precipitation when increasing potential CCN concentrations occurs for drizzling cases. This figure also suggests the suppression of liquid precipitation for the CCN concentrations above 900cm^{-3} allows a significant increase in SCLW mass (Fig. 7) that eventually leads to a significant increase in snow precipitation (Fig 6).

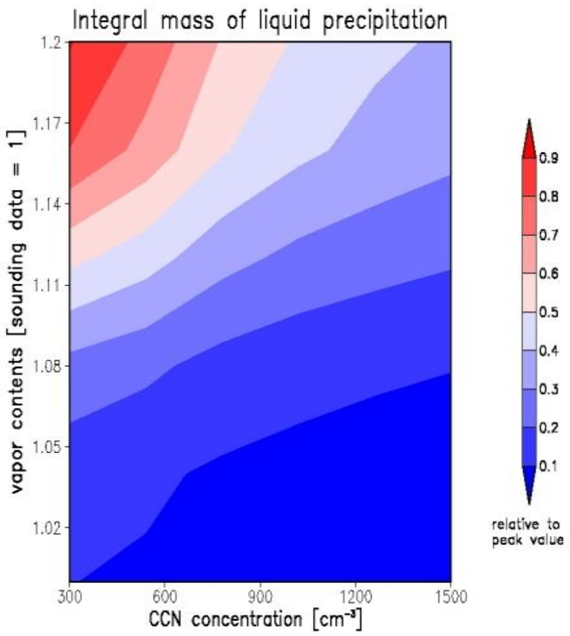

Figure 8. Integral mass of liquid precipitation. Percent increases are relative to the corresponding clean cases.

Liquid precipitation is confined to the first 70 km of the transect, as shown in Fig 9. The two simulations with enhanced vapor contents produced drizzle precipitation; however, considering an air mass more polluted in terms of potential CCN produces an important relative suppression. Higher potential CCN concentrations produces a larger number of smaller cloud droplets, that are less efficient in forming drizzle drops.

Finally, Fig 10 is a cross section of potential CCN effect on the accumulated snow precipitation for selected runs for the largest vapor contents. The polluted ([CCN] = 1500cm-3) case tends to generate higher values of snow precipitation along the transect; the difference in the integral mass of precipitation is slightly above 4%. The downwind displacement of precipitation (spillover) is also visible in the latter figure.

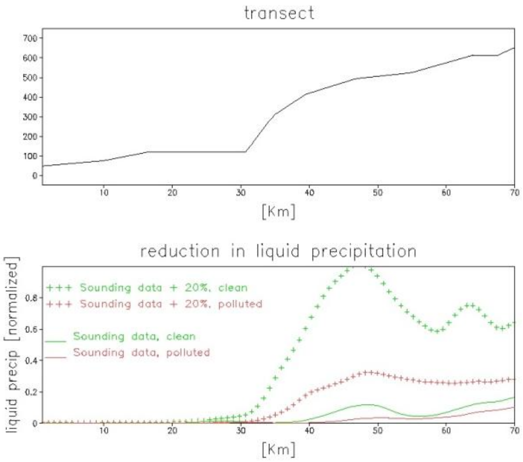

Figure 9. Change in liquid precipitation along the first 70km of the transect for some selected numerical experiments.

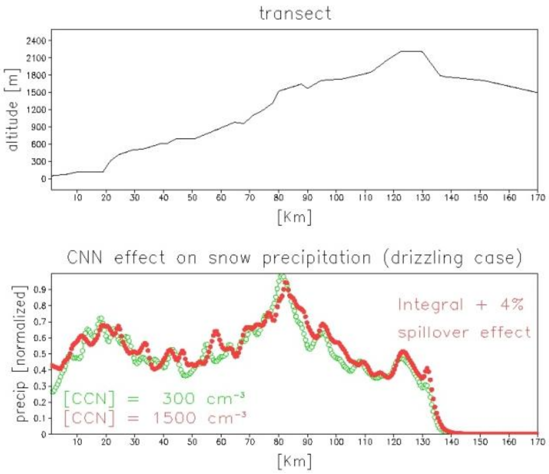

Figure 10 Change in snow precipitation along the transect for high moisture contents.

In summary, high potential CCN concentrations produces the highest SWE along the 2D transect; slightly greater than 4%. The spillover effect is also the dominant response.

5. Conclusion

Two examples of microphysical buffering in wintertime orographic clouds are presented. These systems are much simpler compared to stratocumulus and cumulus clouds as there is no evidence of a dynamic response causing buffering. Nonetheless we see the simple concept that enhanced CCN reduces precipitation cannot be generalized for orographic clouds.

Acknowledgements:

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