Research Article

Sensitivity Studies on the Impact of Dust and Aerosol Pollution Acting as Cloud Nucleating Aerosol on Orographic Precipitation in the Colorado River Basin

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In this study, we examine the cumulative effect of pollution aerosol and dust acting as cloud nucleating aerosol; cloud condensation nuclei (CCN), giant cloud condensation nuclei, and ice nuclei (IN), on orographic precipitation in the Rocky Mountains. We analyze the results of sensitivity studies for specific cases in 2004-2005 winter season to analyze the relative impact of aerosol pollution and dust acting as CCN and IN on precipitation in the Colorado River Basin. Dust is varied from 3 to 10 times in the experiments, and the response is found to be nonmonotonic and depends on various environmental factors. The sensitivity studies show that adding dust in a wet system increases precipitation when IN effects are dominant. For a relatively dry system high concentrations of dust can result in overseeding the clouds and reductions in precipitation. However, when adding dust to a system with warmer cloud bases where drizzle formation is active, the response is nonmonotonic.

1. Introduction

This is the second part of a numerical modeling study using Regional Atmospheric Modeling System (RAMS) [1–3] examining the impacts of varying aerosol pollution and dust on precipitation in the Colorado River Basin (CRB). In Jha [4], we examined the combined effect of dust and aerosol pollution on orographic precipitation in the CRB for 2004-2005 winter season. It was found that dust tends to enhance precipitation primarily by acting as IN, while aerosol pollution reduces water resources in the CRB through the “spillover” effect [5–7], by enhancing cloud droplet concentrations and reducing riming rates. It was found that the combined response to dust and aerosol pollution is a net reduction of water resources in the CRB. Here, we perform sensitivity studies to investigate the impacts of dust and pollution aerosol on different kinds of orographic cloud systems depending on different synoptic forcing and availability of moisture. The new RAMS droplet activation code [4] is

applied in sensitivity studies of a mixed-phase orographic cloud in northwestern Colorado. Section 2 describes the background work and Section 3 describes the methods and experimental design. The results and comparisons among the three case studies have been discussed in Section 4. The conclusions are offered in Section 5 with a summary of the paper in Section 6.

2. Background

The earlier study examines the cumulative effect of dust acting as cloud nucleating aerosol CCN, giant cloud condensation nuclei (GCCN), and ice nuclei (IN) along with anthropogenic aerosol pollution acting primarily as CCN, over the entire Colorado Rocky Mountains from the months of October to April in the year 2004-2005, the snow year. The difference between the old and the new RAMS code has further been discussed. The methods for dust activation as IN in the code, how dust acting as GCCN [8] works in

FIGURE 1: Topography of the area of study where grid 1 is 36 km, grid 2 is 12 km shown in white rectangle, and grid 3 is 3 km in black rectangle (a). Topography of grid 3 with USJ (37.49°N, 106.84°W) marking the Upper San Juan SNOTEL station (b).

RAMS, and how precipitation scavenging is dealt with are described. Letcher and Cotton [9] did a RAMS study on orographic precipitation that suggests that atmospheric CCN concentrations can be reasonably simulated using simplified parameterization of aerosol emissions.

The model setup as well as the initial conditions and the experimental design in the current version of RAMS has also been described in detail in Jha [4]. Kohler theory [10] and its limitations [11] when applied to dust and the corresponding advantages of using the adsorption theory for dust activation scheme have been discussed. In Jha [4], we found that in winter season long simulations, dust primarily acts as IN and increases precipitation over an orographic barrier, but the combined response of dust and pollution aerosols is dominated by the cloud condensation nuclei effects of pollution aerosols which reduced precipitation.

While anthropogenic sources of aerosol particles are changing with human population and technology, natural sources are also impacted. Dust is a relatively large, globally transported natural aerosol source whose production is

impacted by the changes to regional climate, especially the hydrologic cycle. Aerosol particles have also been identified to act on cloud microphysics, through the first and second indirect effects [25–27]. Dust aerosol particles have been shown to serve as CCN, GCCN, and IN [16, 28–31]. Therefore, the presence of dust can possibly alter the formation of warm and mixed-phase clouds on the global scale due to the radiative (direct) and the microphysical (indirect) forcings.

In this paper, we analyze the results of sensitivity experiments to study the microphysics of the orographic cloud and their response to varying dust in different cloud regimes. Dust acting as CCN or IN tends to have contrasting impacts when varied in a wet or dry system.

3. Methods

In this study, we use the Colorado State University (CSU) Regional Atmospheric Modeling System (RAMS) version 6.0 like Saleeby et al. [32]. The 32 km North American Regional Reanalysis (NARR) [12] was used for model initialization and

TABLE 1: RAMS model configuration.

Model aspect	Setting
Grid	Arakawa C grid [1]
	Three grids
	Horizontal grid:
	grid 1: $\Delta x = \Delta y = 36$ km; 150×64 points
	grid 2: $\Delta x = \Delta y = 12$ km; 122×101 points
	grid 3: $\Delta x = \Delta y = 3$ km; 210×170 points
	Vertical grid: Δz variable (75 m at the surface; maximum of 800 m)
Initialization	35 vertical levels
	Model top: ~ 20 km
Time step	10 levels below 1 km
	1° GFS data
Simulation duration	Soil data initialized with ~ 32 km NARR analyses [12]
	30 s
Microphysics scheme	10 days for each case study
	Two-moment bin-emulating microphysics [13–15]
	Water species: vapor, cloud1 and cloud2 cloud drops, rain, pristine ice, snow, aggregates, graupel, and hail
	DeMott et al. [16] heterogeneous ice nucleation and new lookup table including adsorption theory for dust [17]
Aerosol and dust sources	GEOS-Chem and RAMS regional dust sources; dust sources also present in the nonanthropogenic control run
Boundary conditions	Radiative lateral boundary [18]
	Top: rigid lid with a high-viscosity layer aloft to damp gravity waves, by nudging to large-scale analysis or initial conditions [1]
Turbulence scheme	Mellor and Yamada [19]; level 2.5 scheme on grids 1–3; Smagorinsky [20]; the Kain and Fritsch [21] cumulus parameterization applied to grids 1 and 2; convection was resolved explicitly on grid 3
Radiation scheme	Harrington [22], with additions from Stokowski [23]
Surface scheme	LEAF-3 [24]

boundary nudging of the geopotential height, temperature, relative humidity, and winds on grid 1. The initialization data “1° GFS” is used for model initialization on all grids and for nudging the fields on grids 1 and 2. Figure 1(a) shows the 3-grid configuration with filled colors showing the topography. Domain 1 is 36 km and is the entire map, domain 2 is 12 km and is shown by the white box, and domain 3 is the smallest grid with a 3-km spacing shown by black rectangle in the map. Table 1 summarizes the features of the RAMS setup for this study. A look-up table is designed to simulate the competitive interaction of three externally aerosol species: dust, sea spray salt, and ordinary natural soluble aerosol or pollution aerosol. For dust, which is large and largely insoluble, Koehler theory is replaced by an adsorption theory treatment [17]. For given environmental conditions, water adsorption effects on the insoluble dust particles can produce important reductions in the critical size and therefore significantly affect competition. In order to interface the RAMS droplet activation look-up tables with GEOS-Chem [33] for pollution or clean background (no anthropogenic sources) aerosols, the concentration and chemistry (via kappa) are derived by concentration weighting of three internally mixed groups of aerosols predicted by GEOS-Chem (inorganics,

hydrophilic organics, and hydrophobic organics). The kappa and aerosol concentrations so-weighted are then introduced locally to predict the concentration of those potential CCN that are activated to form cloud droplets. In this paper, a series of sensitivity experiments are described to better understand factors influencing the results of impacts of dust and aerosol pollution on seasonal orographic precipitation in the Colorado River Basin [4]. Here we examine specific 10-day periods and perform sensitivity studies to better understand the results from a long term seasonal study. Figure 1(b) shows the topography of the grid 3 with the location of the upper San Juan site in the map (37.49°N , 106.84°W).

In these sensitivity studies, dust concentration was multiplied three times and ten times, respectively, in both the RAMS source dust and the GEOS-Chem ingested dust. As summarized in Table 2, sensitivity experiments included a base study (Experiment #1) in which all dust sources are turned OFF, and only the GEOS-Chem estimated anthropogenic hygroscopic aerosol sources turned ON. Experiment #2 has both the dust and aerosol pollution data ON. Experiment #3 has the aerosol sources ON with dust multiplied by a factor of 3, and Experiment #4 has the aerosol sources

TABLE 2: Sensitivity tests types.

Experiment 1 ald0	Experiment 2 ald1	Experiment 3 ald3	Experiment 4 ald10	Experiment 5 aldin	Experiment 6 aldccn
Aerosol X1 Dust OFF	Aerosol X1 Dust X1 Anthropogenic	Aerosol X1 Dust X3	Aerosol X1 Dust X10	Aerosol X1 Dust can act only as IN	Aerosol X1 Dust can act only as CCN

FIGURE 2: Plot of cloud base temperature for the three case studies. Case Study 3 is dominated by lower cloud bases and hence higher cloud base temperatures. Blue: Case Study 1; purple: Case Study 2; green: Case Study 3.

ON with dust multiplied by a factor of 10. Experiment #5 is a simulation where dust can act only as CCN, and Experiment #6 dust acts only as IN.

3.1. GEOS-Chem Model Description. Dust and hygroscopic aerosol data were initialized from the GEOS-Chem model and regional dust sources in RAMS. The GEOS-Chem data represents long range transport of dust, while dust sources in RAMS represent local sources. GEOS-Chem is a global 3-D chemical transport model (CTM) driven by meteorological input from the Goddard Earth Observing System (GEOS) of the NASA Global Modeling and Assimilation Office and is a by-product of the GEOS-5 [33], which includes wind, convective mass fluxes, mixed layer depths, temperature, clouds, precipitation, and surface properties. The aerosol simulation in the GEOS-Chem includes the sulfate-nitrate-ammonium system [34, 35] and carbonaceous aerosol [36, 37]. Dust emissions are estimated using the Ginoux et al. [38] scheme. The dust simulation in GEOS-Chem and dust size distributions are from Fairlie et al. [39] and Zhang et al. [40], respectively. GEOS-Chem is configured with 47 vertical levels and run with a horizontal resolution of $0.5^\circ \times 0.667^\circ$. GEOS-Chem was run with a spin-up of about 1 month. The aerosol species used in this study consist of three inorganic aerosols (sulfate, nitrate, and ammonia), nine organic aerosols (primary hydrophilic organic carbon, primary hydrophilic black carbon, primary hydrophobic organic carbon, primary hydrophobic black carbon), and 5

secondary organic aerosol (SOA) groups, and dust. These sensitivity experiments are performed for the RAMS using adsorption theory, updated look-up tables, and the DeMott et al. [41] IN nucleation scheme. GEOS-Chem is used to estimate nonanthropogenic and anthropogenic pollution contributions to CCN concentrations.

4. Results and Discussion

4.1. Case Study 1. Case Study 1 was chosen to examine the impact of changing dust on a relatively wet system typical of the main winter periods in the Colorado Mountains. During this period cloud bases were on an average lower than Case Study 2 but higher than Case Study 3 (Figure 2). Cloud base height is defined as the height of the cloud above the mean sea level. Cloud base temperature is defined as the temperature of typical cloud bases in a region. Thus, higher cloud bases correspond to lower cloud base temperatures and vice versa. Hence, it is hypothesized that ice-phase precipitation can be enhanced for low cloud base height by increasing dust acting as IN. In this first case study, the model was run for a period of 10 days, starting on October 22. The different cases that were run for the same time period are as follows: (a) hygroscopic aerosol ON and dust OFF (ald0), (b) hygroscopic aerosol ON and dust ON (ald1), with both dust and hygroscopic aerosol being from anthropogenic sources and the RAMS regional dust sources being also turned on, (c) hygroscopic aerosol ON and dust multiplied 3 times (ald3), (d) hygroscopic aerosol

FIGURE 3: Daily average dust concentration profile for a1d1 for Case Study 1 (a); daily average dust concentration profile for a1d3 for Case Study 1 (b); daily average dust concentration profile for a1d10 for Case Study 1 (c).

FIGURE 4: Plot of precipitation with no dust compared to a1d3, a1d10, a1dccn, a1din for Case Study 1; blue: a1d3, red: a1d10, green: a1din; yellow: a1din (a). Plot of precipitation with no dust compared to a1d1, a1d3, a1d10; blue: a1d1, red: a1d3, green: a1d10 for Case Study 2 (b). Plot of precipitation with no dust compared to a1d1, a1d3, a1d10; blue: a1d1, red: a1d3, gray: a1d10 for Case Study 3 (c).

FIGURE 5: Plot of aggregates for the different sensitivity experiments; red: a1d1, green: a1d3, blue: a1d10.

FIGURE 6: Total precipitable water for grid 3 for Case Study 1 (a); total precipitable water for grid 3 for Case Study 2 (b); total precipitable water for grid 3 for Case Study 3 (c).

FIGURE 8: Plot for comparison of SNOTEL and RAMS snow water equivalent for Case Study 1. Solid red line: RAMS, crossed green line: SNOTEL.

(SWE) for the seasonal trend of precipitation was compared with SNOTEL site observational measurements. SNOTEL (SNOWpack TELEmetry) provides useful high elevation climate information data about real-time precipitation, air temperature, snowpack depth, and snow water content. It makes multiple measurements to provide hourly data per day. SNOTEL uses meteor burst communications technology to collect and communicate data in near-real-time. VHF radio signals are reflected at a steep angle off the ever present band of ionized meteorites existing from about 50 to 75 miles above the earth. We selected SNOTEL sites closest to RAMS grid points and made comparisons with SNOTEL site at San Juan site which is at (37.49°N, 106.84°W). Figure 8 shows the comparison of model data with the SNOTEL [42] observation data at the upper San Juan site and RAMS for Case Study 1. Simulated precipitation mostly stays in agreement with the observational data, especially during the early part of the period but, not surprisingly, less so during the end of the 10-day period.

4.2. Case Study 2. In the second case study, the model was run for a period of 10 days, starting on March 31, 2005, and ending on April 10, 2005. This was a period with higher cloud base heights and is less moist than Case Study 1. The model was run with (a) aerosol ON and dust OFF (a1d0), (b) aerosol ON and dust ON (a1d1), with both dust and aerosol being from anthropogenic sources and the RAMS regional dust sources being also turned on, (c) aerosol ON and dust multiplied 3 times (a1d3), and (d) aerosol ON and dust multiplied 10 times (a1d10). The dust concentration profile is displayed in Figure 9 for the dust ratio a1d1, and the background pollution aerosol concentration varies in space and time in accordance with the GEOS-Chem and RAMS estimates including anthropogenic sources for all the cases. Figure 4(b) shows the ratio of precipitation for (a) a1d1, (b) a1d3, and (c) a1d10 with respect to the case when dust was OFF. It was found that precipitation starts decreasing after adding dust to the system at around April 6. The model was run with dust acting as only CCN and IN, and the precipitation for

TABLE 3: Results of dust sensitivities in the three case studies.

Case study	Precipitation difference (%)	
	D3-D1	D10-D1
1		
Grid 3	0.82	2.255
CRB	0.49	1.290
2		
Grid 3	-4.57	-5.77
CRB	-4.63	-5.62
3		
Grid 3	2.718	-16.907
CRB	1.642	-15.560

those two cases was again compared to the NO dust case. It was found that dust acting solely as CCN yields the least precipitation (Figure 10(a)). This was a case with cloud bases colder than Case Study 1 (Figure 2). The precipitable water available for the system was lower than that for Case Study 1 (Figure 6(b)). A major difference between this and Case Study 1 was the very high zonal southwesterly wind right at the period when the transition happened (Figure 11(b)). Case Study 1 500 mb zonal winds show moderate winds during the period (Figure 11(a)). The strong wind contributes to precipitation drifting into the subsiding region, or “spillover effect,” hence decreasing it. The 500-hPa geopotential height indicates a ridge passing through the region (Figure 7(b)).

4.3. Case Study 3. The third study was started on October 2 and run for duration of 10 days. Dust was varied in different experiments and pollution aerosol varied spatially and temporally according to GEOS-Chem and RAMS estimates following the pattern in Table 3, and precipitation difference was observed for the duration. This was a period with very warm cloud bases temperatures and lower cloud base height with greater availability of moisture. It is a relatively anomalously

FIGURE 9: Daily average dust concentration profile for ald1 for Case Study 2.

FIGURE 10: Plot of precipitation with no dust compared to ald1ccn and ald1in; yellow line: ald1in; purple line: ald1ccn (a). Plot of precipitation with no dust compared to dust acting only as IN and CCN; purple: ald1ccn, yellow: ald1in for Case Study 3 (b).

warm cloud base period relative to the main winter season in Colorado. Hence, it is important to see how changing dust impacts precipitation for the period. When dust was increased 3 times, precipitation increased slightly (2.7%), but when dust was increased 10 times, precipitation decreased by -16.9% in the CRB (Figure 12). Figure 4(c) shows the comparison of the experiments as dust concentration is increased for ald1, ald3, and ald10. The total precipitable water indicated it as a very wet period (Figure 6(c)). When dust is increased 10 times, the precipitation in the system is reduced due to overseeding of IN producing numerous small ice crystals. Figure 13 shows the pristine ice concentrations when dust increased from ald1 (Figure 13(a)) to ald10

(Figure 13(b)). We can see higher concentrations of pristine ice when dust is tenfold. The temperature profile suggests a warmer cloud base as compared to Case Study 1. The system is much wetter than Case Study 2 (Figure 7(c)), and the temperature profile suggests warmer cloud bases in this case compared to the system in both Case Study 1 and Case Study 2 initially (Figure 2). The total mass of the water in the drizzle category reduces with increasing dust, since dust acting as CCN suppresses collision and coalescence [43]. Thus, the availability of supercooled liquid water (SLWC) that could be transferred to snow by riming is increased here (Figure 14). The curve has been normalized by the maximum value. Colder cloud temperatures prevail towards the later part of

FIGURE 11: (a) 500 mb zonal wind speed for Case Study 1 (b). 500 mb zonal wind speed for Case Study 2.

FIGURE 12: Daily average dust concentration profile for a1d10 for Case Study 3.

the period, and dust acting as CCN (Figure 10(b)) was more dominant. Despite higher supercooled liquid water contents with higher dust concentrations, high dust concentrations produced numerous small droplets which suppressed riming and led to a reduction in precipitation, a nonmonotonic response when dust is increased 10 times. Carrió and Cotton [44] performed an idealized study and varied both CCN concentrations and the low-level moisture in the Sierra Nevada mountains in a 2D modeling study with RAMS. They observed that for low moisture amounts (i.e., clouds with high cloud bases), increasing CCN decreased the integral

mass of snow precipitation. However, for lower cloud bases (higher low-level moisture amounts) or cloud with warmer cloud base, they simulated a nonmonotonic behavior with enhanced ice-phase precipitation.

In a different experiment, other than these three case studies, the model was run to determine the change in response in precipitation between anthropogenic and nonanthropogenic sources of dust and pollution aerosol, and it was found that anthropogenic or nonanthropogenic sources of dust and aerosol pollution have varying impact on the precipitation. In this case, they had a similar response.

FIGURE 13: Pristine ice concentration of Case Study 3 for ald1 (a), ald10 (b).

Figure 15 shows the total precipitation response when the model was run for the following cases: (a) aerosol ON and dust ON (ald1), with both dust and aerosol being from anthropogenic sources, (b) aerosol ON and dust ON (ald1), with both dust and aerosol being from nonanthropogenic sources, (c) aerosol ON and dust OFF (ald0), (d) aerosol ON and dust multiplied 3 times (ald3), and (e) aerosol ON and dust multiplied 10 times (ald10). It was found that the precipitation was the highest for the case (e) ald10 and the least for the no dust case (neither anthropogenic nor nonanthropogenic sources). The precipitation for ald3 was less than ald1. However, in yet another case study anthropogenic aerosol had a bigger impact on precipitation (figure not shown here). Hence, it is a nonmonotonic response and

we need to do further studies based on other environmental factors and feedback involved.

5. Discussion

We performed a series of numerical experiments with the objective of examining the CCN and IN effects and identifying the environmental conditions for which they become dominant. Dust concentration was varied in these three different periods to examine the response on the precipitation in an orographic cloud system. It was found that adding dust in a relatively wet storm (Case Study 1) results in dust increasing precipitation largely due to it acting as IN (Table 3). This is due to the greater amounts of supercooled liquid

FIGURE 14: Comparison of total mass of water in drizzle category; black: ald1, pink: ald3, green: ald10.

FIGURE 15: Plot of precipitation for (a) ald1, (b) ald0, (c) nonanthropogenic pollution aerosol, (d) ald3, (e) ald10.

water of the system available to enhance precipitation during this period. However, in a relatively dry storm system (Case Study 2), the clouds were “overseeded” with IN, which led to a decrease in precipitation. It is also evident that the background CCN concentration did not play significant role during the sensitivity runs as it remains low throughout the period of change in precipitation. Dust acts as CCN and hence decreases precipitation after April 6 in Case Study 2. Case Study 3 was a period with very warm cloud bases temperatures and lower cloud base heights with greater availability of moisture, which supported an active drizzle formation process. Dust acting as CCN, suppressed drizzle formation and increased SLWC, enhancing riming. The response is not monotonic with dust. The reason is that, for moderate dust concentrations, aerosol pollution dominates

FIGURE 16: Plot of aerosol concentrations for the three case studies. Case Study 3 is the one that has the highest concentration of aerosols.

but, owing to warm cloud bases, drizzle formation is active. For higher concentrations of dust, drizzle acting as CCN suppresses warm rain processes, SLWC increases, and ice-phase precipitation is enhanced. For dust enhanced 10x, SLWC is enhanced, but riming is suppressed owing to small droplet sizes; therefore, we see lower precipitation amounts in ice-phase when dust is enhanced 10 times in Case study 3 with higher cloud base temperatures. Case Study 3 had also the highest concentration of aerosols as seen in Figure 16.

Changes in microphysics impacts the precipitation of the system, but the dynamical forcing of a storm system which affects wind strength and temperature of cloud base and water content of the storm has a larger impact on the system. More studies need to be done to analyze the response in different cloud regimes and geographical locations.

It is important to keep in mind that results of Jha [4] show that dust is a secondary contributor to precipitation over the CRB as anthropogenic pollution dominates over the entire winter season, contributing total winter season precipitation loss of 5,380,00 acre-feet of water for the ~6.5 months of simulation.

6. Summary

The main conclusions from the results are as follows:

(i) Sensitivity studies suggest that the impact of dust in a system is largely dependent on the synoptic scale flow and the amount of moisture available for a case study. Increasing amounts of dust has a larger impact on wet weather systems.

(ii) In Case Study 1, a wet system, dust increases precipitation in the CRB by 0.49% when increased 3 times and 1.29% when increased 10 times. Therefore, in Case 1, the cloud base heights are higher than Case Study 3 and lower than Case Study 2, and adding dust as IN increased precipitation. The dust IN effects are dominant and there is more precipitation when dust acts only as IN, but the increase is not huge.

(iii) In Case Study 2, dust decreases precipitation in the CRB by -4.63% when increased 3 times and -5.62% when increased 10 times. This system has the least precipitable water out of the three case studies. Other meteorological factors like high southwesterly wind flow could possibly favor enhanced blow-over of precipitation and hence lead to overseeding of the clouds.

(iv) In Case 3, cloud bases are lower, so the base temperatures are warmer, an active drizzle formation process is present, and dust CCN effects are more dominant. Therefore, we see nonmonotonicity in response and suppression of drizzle formation, which is similar to the results of Carrió and Cotton [44].

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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