DOES DUST AND POLLUTION AEROSOL ACTING AS CLOUD NUCLEATING PARTICLES APPRECIABLY IMPACT WATER RESOURCES N THE COLORADO RIVER BASIN?

William R. Cotton[1] and Vandana Jha[2]

ABSTRACT

Over the last decade, there have been numerous modeling and observational studies which suggest that anthropogenic aerosol pollution such as emitted by many industries, automobile exhaust, and coal-fired power plants, are quite hygroscopic and as such can serve as particles on which cloud droplets form or what we call cloud-condensation-nuclei (CCN). In the case of wintertime orographic clouds such as in Colorado, too many CCN lead to numerous cloud droplets which are so small that they suppress rain formation by collision and coalescence of cloud droplets (not very important for those clouds), but more importantly suppress snow formation via cloud droplets being collected by ice particles or what we call riming. Previous modeling studies by our group as well as other researchers suggest that aerosol pollution will result in reduced precipitation in the Colorado mountains, particularly in relatively wet storms. Another aerosol source important to precipitation processes is wind-blown dust. While some dust particles can serve as CCN, their numbers are so few that they are not competitive with natural or pollution aerosols in rain formation or ice particle riming. But dust is also known to be the most important natural source of ice nuclei (IN). Thus, long-range transported dust and locally produced in say the four corners region flow into the Colorado mountains and essentially seed those clouds with IN, much like purposely-produced cloud seeding, and enhance precipitation from wintertime orographic clouds. Here we present the first attempt to examine the combined impact of both aerosol pollution and dust on precipitation over the Colorado mountains for an entire snow year, the months of October to April in the year 2004-2005, which is a relatively wet snow year.
(KEYWORDS: dust, pollution, aerosol, cloud condensation nuclei, ice nuclei, Colorado)

INTRODUCTION

Here, we examine the possible impacts of anthropogenic aerosol and dust acting as cloud nucleating aerosol on water resources in the Colorado River Basin (CRB). Much of human activity such as energy production by fossil fuels, automotive exhaust, home heat production, and many industries produce small (less than 0.2 micrometers), hygroscopic (or water absorbing) aerosols (Jha, 2016). Compared to a clean atmosphere, these particles are more numerous and act as cloud droplet forming nuclei, or what we call cloud condensation nuclei (CCN). As a result, the cloud droplets that form in a cloud are more numerous in a polluted atmosphere compared to a clean atmosphere. For a given amount of liquid water, these droplets are smaller and are less likely to rapidly form precipitation particles by droplet collision and coalescence. However, this process is not very active in cold, wintertime orographic clouds. The major precipitation forming process in those clouds is ice crystal growth by vapor deposition and ice particle collection of supercooled cloud droplets, a process we call riming growth.

Borys et al. (2000, 2003) showed that ice particles differed substantially in structure in a clean atmosphere versus a polluted one (see Figure 1). They hypothesized that wintertime orographic precipitation will be reduced in a polluted atmosphere relative to a clean one. In a modeling study using the Colorado State University Regional Atmospheric Modeling System (RAMS; Cotton et al., 2003), Saleeby et al. (2009) found that reduced riming lowered snow water equivalent precipitation amounts on the windward side of the mountain barrier and increased it on the lee slopes. In the case of the Park Range, the "spillover effect" led to a downstream shift of precipitation from the Pacific watershed to the Atlantic watershed further contributing to a reduction of precipitation in the Colorado River Basin (CRB). Spillover effect is defined as the shift of precipitation from the windward to the leeward side of a mountain due to redistribution of precipitation particles. Lightly rimed ice particles have lower fall velocities than heavier rimed particles. Saleeby et al. (2010) also showed that this effect was only important for relatively wet storms where riming is important. Subsequently, Saleeby et al. (2011) estimated the total change

Presented Western Snow Conference 2018
[1] Department of Atmospheric Sciences, Colorado State University, Fort Collins, CO 80523
[2] NASA Ames Research Center, Universities Space Research Association Moffett Field

in precipitation for all of western Colorado due to aerosol pollution for a 60-day period for four different seasons. These simulations were performed for assumed high and low values of aerosol acting as CCN. While little change in total precipitation was found, a major shift in precipitation downwind, or spillover effect, was simulated owing to aerosol pollution. In that study, the biggest loser was the CRB with as much as 522,000 acre-ft lost for a 60-day period in 2005

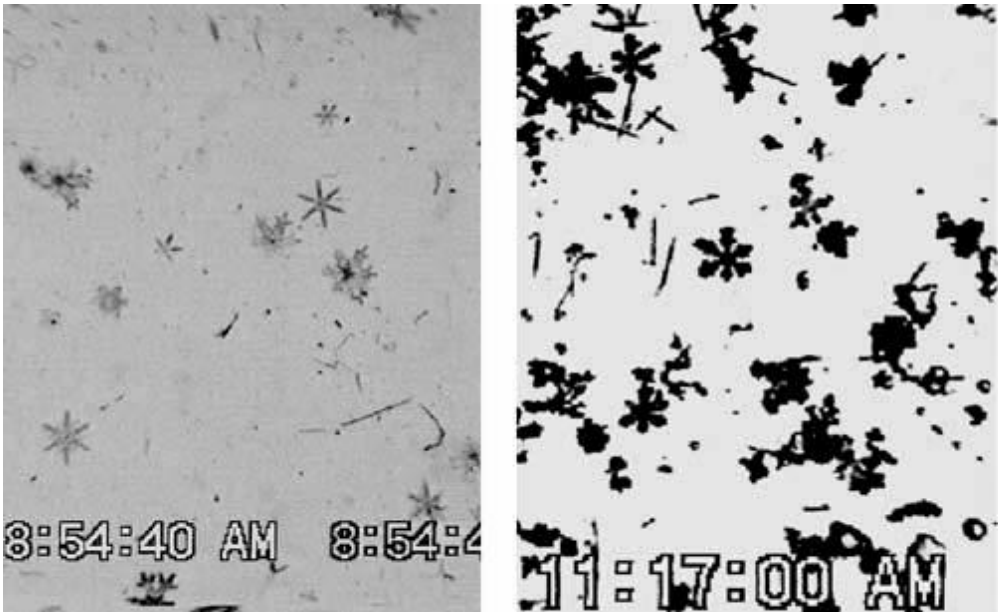

Figure 1. Example of the influence of aerosol on ice crystal structure. Left panel light riming in a polluted atmosphere and right panel heavy riming in a clean atmosphere (Borys et al., 2000, 2003).

In this study, we examine the combined impact of anthropogenic aerosol and dust on orographic precipitation and the water resources in the CRB for an entire snow year. Dust is known to act as a good ice nuclei (IN) (Schaefer, 1949, 1954; Isono et al., 1959; Roberts and Hallett, 1968; Hung et al., 2003; Gagin, 1965; Sassen et al., 2003; DeMott et al., 2003, 2009). Considering that the basis behind cloud seeding is to enhance precipitation by enhancing IN concentrations (Cotton and Pielke, 2007), we anticipate that dust serving as IN will enhance precipitation in wintertime orographic clouds. Muhlbauaer and Lohmann (2009) did a 3D idealized case study of mixed phase orographic clouds and found that in the simulations with dust aerosol, the dust aerosols serve as ice nuclei and hence lead to an early ice phase initiation and enhanced riming which leads to enhancement of orographic precipitation. If dust becomes coated with hygroscopic material or originates over dry lake beds, dust can serve as giant cloud condensation nuclei (GCCN) which when wetted can result in larger cloud droplets and thereby enhance the warm-cloud collision and coalescence process and ice particle riming. Dust serving as GCCN should enhance precipitation (Levin et al., 1996), thus affecting precipitation in the same direction as I N . However, the major impact of GCCN is on enhancing the warm-rain collision and coalescence process, a process that is not very active in wintertime orographic clouds in Colorado. But smaller dust particles coated with hygroscopic material can enhance droplet concentrations, leading to numerous smaller droplets and decreasing collision and coalescence of droplets and ice particle riming. Thus, dust functioning as CCN will work in opposition to its activity as GCCN and IN and suppress precipitation much like pollution aerosol. However, dust concentrations are much lower than anthropogenic or other natural sources of CCN. We therefore anticipate that dust serving as IN will dominate over its affects as GCCN and CCN. No one to our knowledge has examined the combined effects of dust serving as IN, GCCN, and CCN on precipitation or on water resources in the CRB. Sensitivity studies discussed by Jha et al. (2018) revealed that additional dust in a wet system increases precipitation. For a relatively dry system high concentrations of dust can result in over-seeding the clouds and leading to reductions in precipitation. However, when adding dust to a system with warmer cloud bases where drizzle formation is active, the response is non-monotonic. But, overall dust tends to enhance precipitation in wintertime orographic clouds in Colorado. The focus of this study is on the combined impacts of anthropogenic aerosol and dust acting as cloud nucleating aerosol on wintertime orographic precipitation in the Colorado Mountains.

AEROSOL SOURCES

Long range transported aerosol (both anthropogenic and natural sources) and dust is simulated using the GEOS-Chem model v9.02 (http://geos-chem.org; Bey et al. 2001). GEOS-Chem is a chemical transport model which uses assimilated meteorological data from the NASA Goddard Earth Observation System (GEOS) version 5. In addition, local dust sources were estimated using a dust source and transport module incorporated into RAMS (Lerach,2010; Lerach and Cotton, 2018), is based on that of Ginoux et al. (2001), which advects lofted dust in two size bins; accumulation mode and coarse mode. The fine mode dust median radius was set to 0.2µm, and the coarse mode dust median radius was set to 3.0 µm. GEOS-Chem was run for the entire winter 2004-2005 season.

RAMS DYNAMICAL SETUP

Table 1 summarizes the features of the RAMS setup for this study. Figure 2 shows the grid configuration used. The outermost grid, Grid 1 has 36 km grid spacing and consists of almost all of North America. Grid 2 is displayed in the blue color and has a grid spacing of 12 km. The innermost grid is Grid 3, displayed in red with a grid spacing of 3 km. The 32km North American Regional Reanalysis (NARR) (Mesinger et al., 2006), was used for model initialization and boundary nudging of the geopotential height, temperature, relative humidity, and winds.

Table 1. RAMS model configuration

Grid	Arakawa C grid (Cotton et al., 2003); 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) 35 vertical levels Model top: ~20 km, 10 levels below 1 km
Initialization	1^{o} GFS data Soil data initialized with ~32 km NARR analyses (Mesinger et al., 2006)
Time step	30 s
Simulation duration	6.5 months
Microphysics scheme	Two-moment bin-emulating microphysics (Saleeby and Cotton, 2004, 2008, 2009) Water species: vapor, cloud1 and cloud2 cloud drops, rain, pristine ice, snow, aggregates, graupel, and hail, (DeMott et al., 2014) heterogeneous ice nucleation, and new lookup table including adsorption theory for dust (Kumar et al. 2011)
Aerosol & Dust Sources	GEOS-CHEM and RAMS regional dust sources; Dust sources also present in the non-anthropogenic control run
Boundary conditions	Radiative lateral boundary (Klemp and Wilhelmson, 1978) Top: Rigid lid with a high-viscosity layer aloft to damp gravity waves, by nudging to large-scale analysis or initial conditions (Cotton et al., 2003)
Turbulence scheme	Mellor and Yamada, 1974; level 2.5 scheme on grids 1-3; (Smagorinsky, 1963; Kain and Fritsch, 1993) cumulus parameterization applied to grids 1 and 2, convection was resolved explicitly on grid 3
Radiation scheme	Harrington, 1997; with additions from Stokowski, 2005
Surface scheme	LEAF-3 (Walko et al. 2000)

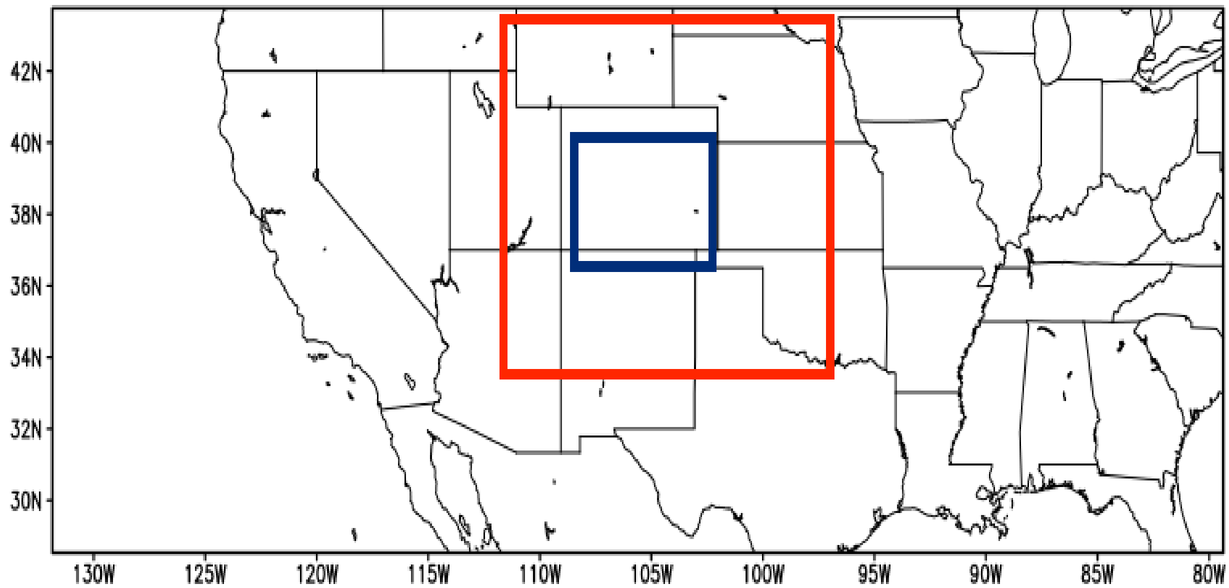

Figure 2. The 3-grid configuration is shown here. Grid 1 has the 36 km grid spacing and comprises of the entire outer boundary in the map. Grid is 12 km and is shown in blue rectangle. Grid 3 is of 3 km spacing and is displayed in red rectangle.

RAMS was run explicitly representing liquid and ice-phase precipitation processes, including rather sophisticated representation of nucleation of aerosol to form cloud droplets and ice crystals (Jha, 2016; Jha et al., 2018). The model was run for the entire 2004-2005 winter season, in 10-day increments with each 10-day period re-initialized with re-analysis data, and the coarse lateral boundaries nudged with the large-scale reanalysis data for the period. The control run included both locally and long-range transported dust. It included only non-anthropogenic CCN sources. The "dirty" run was the same as the control except that anthropogenic sources of CCN were included. For further details on the model setup and physics used see Jha (2016).

Figure 3 illustrates the daily average aerosol concentrations simulated by GEOS-Chem for the period. The aerosols include sulfate, nitrates, ammonium, sea-salt, hydrophobic black carbon, hydrophobic organic carbon, and five groups of secondary aerosols.

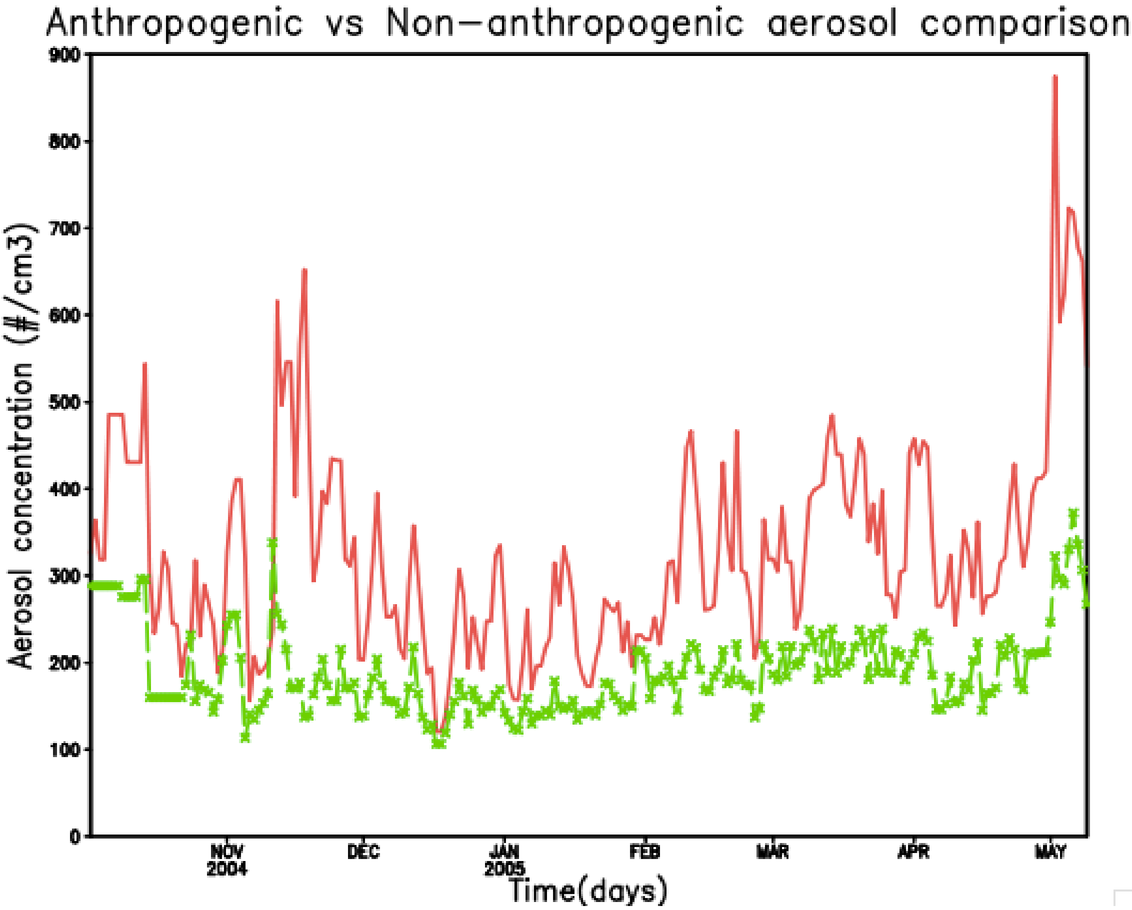

Figure 3. Geos-Chem simulated aerosol concentrations for the 2004-2005 winter season. Anthropogenic aerosols are in red (top line), and non-anthropogenic aerosols are in green (bottom line).

RESULTS

Figure 4 illustrates the total precipitation differences over the fine-grid domain for the 2004-2005 winter season. One can see substantial reductions in precipitation on the windward side of the CRB, while there is some evidence of increases leeward of the CRB. Using our best estimates of IN nucleation scheme and dust acting as CCN, the combined effects of anthropogenic pollution and dust can lead to a decrease 2.1 % for the CRB (5,380,000 acre-feet) for a period of almost 7 months. This is an appreciable amount of water. To put this in perspective, this loss of precipitation corresponds to roughly 72% of the total allocated water resources for the upper Colorado River Basin in the 1922 Colorado River Compact.

CONCLUSION

Overall, anthropogenic aerosol pollution contributes to a net reduction in water resources in the CRB, but dust acts to moderate that amount.

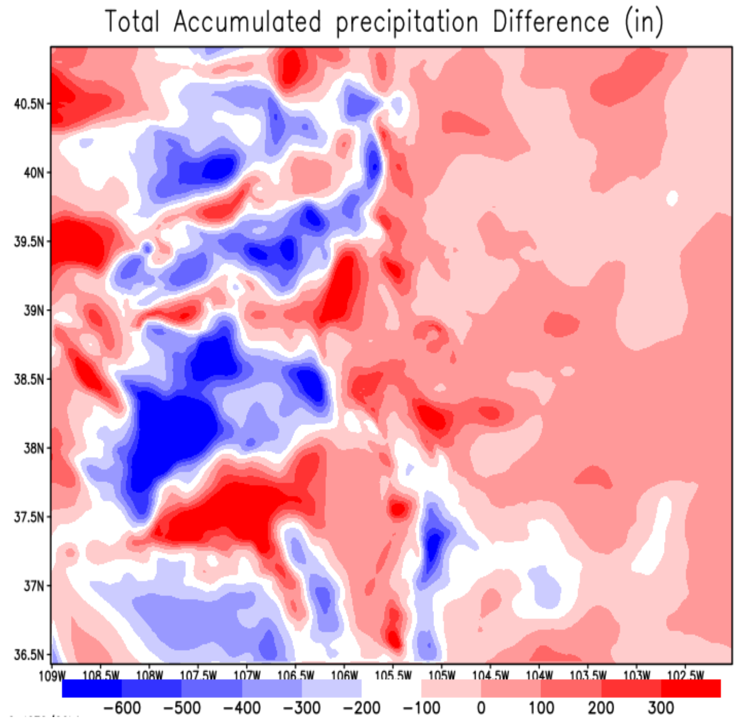

Figure 4. Precipitation differences in inches between runs with anthropogenic sources and runs with no anthropogenic aerosol sources as a function of latitude and longitude over the fine-mesh domain.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation Division of Atmospheric Sciences grant AGS 1138896.

REFERENCES

Borys, R. D., D. H. Lowenthal, S. A. Cohn, and W. O. J. Brown. 2003. Mountaintop and radar measurements of anthropogenic aerosol effects on snow growth and snowfall rate. *Geophys. Res. Lett.*, **30**, 1538.

Borys, R. D., D. H. Lowenthal, and D. L. Mitchell. 2000. The relationships among cloud microphysics, chemistry, and precipitation rate in cold mountain clouds. *Atmos. Environ.*, **34**, 2593–2602.

Cotton, W.R., R.A. Pielke, Sr., R.L. Walko, G.E. Liston, C.J. Tremback, H. Jiang, R.L. McAnelly, J.Y. Harrington, M.E. Nicholls, G.G. Carrió, and J.P. McFadden. 2003. RAMS 2001: Current status and future directions. *Meteor. Atmos Physics*, **82**, 5-29.

Cotton, W.R., and R.A. Pielke. 2007. *Human Impacts on Weather and Climate,* 2nd Edition. Cambridge Univ. 2007.

DeMott, P. J., Sassen, K., Poellot, M. R., Baumgardner, D., Rodgers, D. C., Brooks, S. D., A.J. Prenni, and S. M. Kreidenweis. 2003. African dust aerosols as atmospheric ice nuclei. Geophys. Res. Lett. 30, 1732, doi:10.1029/2003GL017410.

DeMott, P. J., M. D. Petters, A. J. Prenni, C. M. Carrico, S. M. Kreidenweis, J. L. Collett, and H. Moosmuller. 2009, Ice nucleation behavior of biomass combustion particles at cirrus temperatures. *J. Geophys. Res.*, **114**, D16205, doi: 10.1029/2009jd012036.

DeMott, C. A., C. Stan, D. A. Randall, and M. D. Branson, 2014. Intraseasonal variability in coupled GCMs: The roles of ocean feedbacks and model physics. *J. Climate,* **27**, 4970–4995.

Gagin, A. 1965. Ice Nuclei, their physical characteristics and possible effect on precipitation initiation. *Proc. Int. Conf. On Cloud Physics*, Tokyo and Sapporo, Japan, 155-162.

Ginoux, P., M. Chin, I. Tegen, J. M. Prospero, B. Holben, O. Dubovik, and S. J. Lin. 2001. Sources and distributions of dust aerosols simulated with the GOCART model. *J. Geophys. Res.*, **106**, 20255–20274.

Harrington, J. Y. 1997. The effects of radiative and microphysical processes on simulated warm and transition season Arctic stratus. Ph.D. dissertation, Dept. of Atmospheric Science, Colorado State University, 289 pp.

Hung, H. M., A. Malinowski, and S. T. Martin. 2003. Kinetics of heterogeneous ice nucleation on the surfaces of mineral dust cores inserted into aqueous ammonium sulfate particles. *J. Phys. Chem.*, 107, 1296-1306.

Isono, K., M. Komabayasi, and A. Ono. 1959. Volcanoes as a source of atmospheric ice nuclei. *Nature*, **183**, 317-318.

Jha, V. 2016. Examination of the potential impacts of dust and pollution aerosol acting as cloud nucleating aerosol on water resources in the Colorado river basin. Dissertation, Colorado State University, 90 pp., https://dspace.library.colostate.edu/handle/10217/173399

Jha, V., W.R.Cotton, G. G. Carrió, and R.Walko. 2018. Sensitivity studies on the impact of dust and aerosol pollution acting as cloud nucleating aerosol on orographic precipitation in the Colorado River basin, Advances in Meteorology, V 2018:3041893, doi: 10.1155/2018/3041893

Kain, J. S., and J. M. Fritsch. 1993. Convective parameterization for mesoscale models: The Kain–Fritsch scheme., *The Representation of Cumulus Convection in Numerical Models*, *Meteor. Monogr.*, No. 24, Amer. Meteor. Soc., 165–170.

Klemp, J. B., and R. B. Wilhelmson. 1978. Simulations of right-and left-moving storms produced through storm-splitting. *J. Atmos. Sci.*, **35**, 1097-1110.

Kumar P., I. N. Sokolik, and A. Nenes. 2011. Measurements of cloud condensation nuclei activity and droplet activation kinetics of wet processed regional dust samples and minerals. *Atmos Chem Phys.*, **11**, 8661–8676, doi:10.5194/acp-11-8661-2011.

Lerach, D. G. 2012. Simulating Southwestern U.S. desert dust influences on severe, tornadic storms. PhD dissertation, Dept. of Atmospheric Sciences, Colorado State University, pp. 353.

Lerach, D. G., and W. R. Cotton. 2018. Simulating southwestern U.S. desert dust influences on supercell thunderstorms. Atmos. Res., 204, 78-93.

Levin, Z., E. Ganor, and V. Gladstein. 1996. The effects of desert particles coated with sulfate on rain formation in the eastern Mediterranean. *J. App. Meteor.*, **35**, 1511-1523.

Mellor, G. L., and T. Yamada. 1974. A hierarchy of turbulence closure models for planetary boundary layers. *J. Atmos. Sc.*, **31**, 1791-1806.

Mesinger, F., and Coauthors. 2006. North American regional reanalysis. *Bull. Am. Meteorol. Soc.*, **87**, 343–360.

Muhlbauer, A., and U. Lohmann. 2009. Sensitivity studies of aerosol-cloud interactions in mixed-phase orographic precipitation. *J. Atmos. Sci.*, **66**, 2517-2538.

Roberts, P., and J. Hallett. 1968. A laboratory study of ice nucleating properties of some mineral particulates. *Q. J. R. Meteorol. Soc*., 94, 25-34.

Saleeby, S. M., and W. R. Cotton. 2004. A large droplet mode and prognostic number concentration of cloud droplets in the Colorado State University Regional Atmospheric Modeling System (RAMS). Part I: Module descriptions and supercell test simulations. *J. Appl. Meteor.*, **43**, 182-195.

Saleeby, S. M., and W. R. Cotton. 2008. A binned approach to cloud-droplet riming implemented in a bulk microphysics model. *J. Appl. Meteorol.*, **47**, doi:10.1175/2007JAMC1664.1.

Saleeby, S. M., W. R. Cotton, D. Lowenthal, R. D. Borys, and M. A. Wetzel. 2009. Influence of cloud condensation nuclei on orographic snowfall. *J. Appl. Meteor. Clim*., **48**, 903-922.

Saleeby, S. M., W. R. Cotton, and J. D. Fuller. 2010. The cumulative impact of cloud droplet nucleating aerosols on orographic snowfall in Colorado. *J. Appl. Meteor. Clim*., **50**, 604-625.

Saleeby, S. M., W. R. Cotton, and D. Lowenthal. 2011. Impact of aerosols on the microphysical processes with an orographic cloud environment. AMS Annual Meeting, Seattle, WA.

Sassen, K., P. DeMott, J. Prospero, and M. Poellot. 2003. Saharan dust storms and indirect aerosol effects on clouds: Crystal-face results. *Geophys. Res. Lett.*, **30**, 1633, doi:10.1029/2003GL017371.

Schaefer, M. B. 1954. Some aspects of the dynamics of populations, important for the management of the commercial marine fisheries. *Inter. Am. Trop. Tuna Comm. Bull.*, **1**, 27-56.

Schaefer, V. J. 1949. The formation of ice crystals in the laboratory and the atmosphere. *Chem. Rev.*, **44**, 291-320.
Smagorinsky, J., 1963: General circulation experiments with the primitive equations, i. the basic experiment. *Monthly Weather Rev.*, **91**, 99-164.

Stokowski, D. M. 2005. The addition of the direct radiative effect of atmospheric aerosols into the regional atmospheric modeling system (RAMS). M.S. thesis, Colorado State University, Department of Atmospheric Science, Fort Collins, CO.

Walko, R. L., and Coauthors. 2000. Coupled atmosphere-biophysics-hydrology models for environmental modeling. *J. Appl. Meteor.*, **39**, 931-944.