1.10 **THE EFFECTS OF ATMOSPHERIC PARTICLE CONCENTRATION ON CLOUD MICROPHYSICS OVER ARECIBO**

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1. INTRODUCTION

The interaction between clouds and aerosols is being recognized as one of the major factors controlling cloud development and precipitation patterns over local, regional, and even global scales. Given the complexity of the problem due to the intricate physics of cloud formation and development, in-cloud turbulence, aerosol chemistry and dynamics, among other topics, progress in this area has been hindered, or over-simplified for a long time. During recent years there have been significant advances in cloud microphysics, cloud modeling schemes, cloud resolving atmospheric models, and in computing capabilities that could improve our ability to predict the effects of atmospheric particles (AP) on different cloud microphysical fields over tropical regions.

The main mechanism where AP influences the development of clouds and precipitation, is when new particles serving as condensation nuclei increase the number of small droplets. The spectrum of these new drops depends on the characteristic of the AP. The higher concentration damps the growth of existing cloud droplets by diffusion because there will be more competition for the water vapor available in the atmosphere. This, in turn, affects the possibility of growth by collision and coalescence because the effective drop radius for this process to occur cannot be reached. Khain et al. (2000) reported several studies in polluted areas over Thailand and Indonesia where observed smoked clouds do not precipitate altogether, having narrow spectra of small droplets. At the same time, similar clouds precipitate in unpolluted air in only 15–20 min after their formation. Similar results were found in continental clouds of Amazon smoky areas (Kaufman and Nakajima 1993).

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The intention of this note is to demonstrate an improvement in our ability to predict precipitation in tropical coastal regions by using a better representation of cloud microphysics and in local AP spectrum. With the aide of a cloud resolving mesoscale model and detailed AP observations by the Arecibo Observatory (AO) we present in this work the ability of a mesoscale model to simulate a precipitation event identified in the region of interest. A second set of model runs will try to explain the dissimilarity in resolved total precipitation between the different predictions of the same precipitation event. The area of study is located on the north coast of the Caribbean island of Puerto Rico, centered on the Arecibo Observatory (18.35ºN, 66.75ºW), as shown in the model grids used, Figure 1.

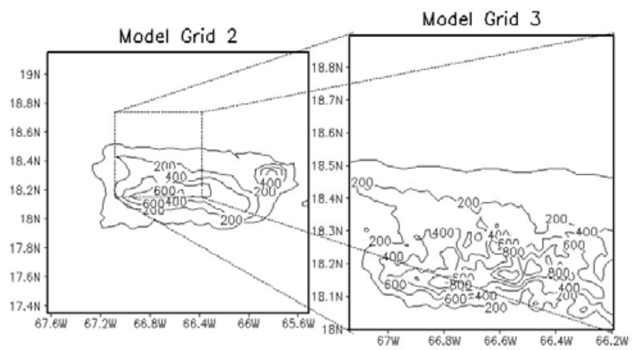

Figure 1 Topography of the Island of Puerto Rico (contour int. 200m) and area centered on the AO where the study was performed (expanded inset, contour int. 200m)

2. ATMOSPHERIC PARTICLE MEASUREMENTS

The aerosol measurements generally were made from two locations in northwest Puerto Rico – at the Arecibo Observatory and near the town of Aguadilla (18.50oN, 67.13oW) that represent rural inland and suburban coastal conditions, respectively. The instrument used is a five-channel portable Sun photometer called the Microtops II manufactured by Solar Light, Inc (Ichoku et al 2002). The channels are filtered for the wavelengths 380, 440, 500, 675, and 870 nm, the aerosol optical thickness data determined from six, sometimes seven, of the wavelengths observed. These span the optical spectrum from the near-UV to the near-IR, which allows us to extract particle sizes to almost three orders of magnitude.

From as early as March 2002, measurements of transmitted atmospheric radiance, and thus, the aerosol optical thickness (AOT) at the wavelengths mentioned above have been taken, with an average of two and three observations per day (usually at 09:00, 12:00, and 15:00 LT where solar zenith angles are less than about 45º). These AOT data can be inverted to estimate the size of the particles that are responsible for the extinction of solar radiation, and this provides better estimates for the cloud condensation nuclei to be used in the climate models. The code developed by King et al. (1978) and Dubovik and King (2000) was used for the inversions. The range of the inversion spans the smaller, Aitken-type particles (r < 0.1 μm) through the Large (0.1 ≤ r ≤ 1.0 μm) and Giant (r > 1.0 μm) aerosol classifications for particle radius, r. The lower limit of the inversion technique obtained overlaps with what might be considered true cloud condensation nuclei (CCN) and as such, provides a good estimate of the seasonal behavior of CCN in the tropics. An example of estimated aerosol particle size distribution for three separate days in 2002 is shown in Figure 2. Figure 3 shows the annual variation of the number density for several particle radii extracted from the inversion algorithm. The range is logarithmic and skewed toward the smaller radii.

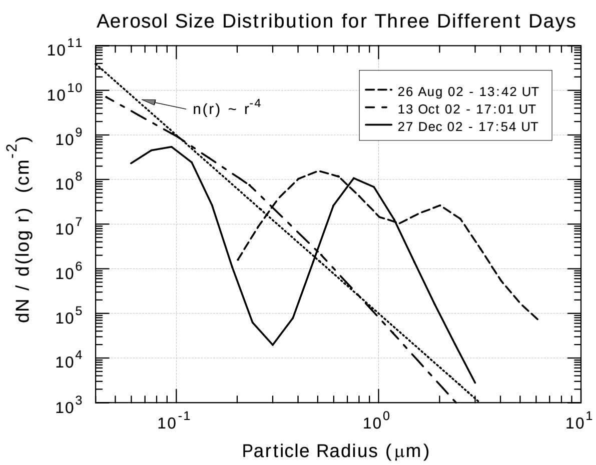

Figure 2 Log-radius number distribution for aerosols as a function of particle radius measured from northwest Puerto Rico on three days

3. MODEL DESCRIPTION

The mesoscale model used in this work is the Regional Atmospheric Modeling System (RAMS), developed at Colorado State University (Pielke et al. 1992, Cotton et al. 2003). RAMS is a highly versatile numerical code developed for simulating and forecasting meteorological phenomena. The atmospheric model is built around the full set of non-hydrostatic, dynamical equations that governs atmospheric dynamics and thermodynamics, plus conservation equations for scalar quantities such as mass and moisture. These equations are complemented by a large selection of parameterizations available in the model.

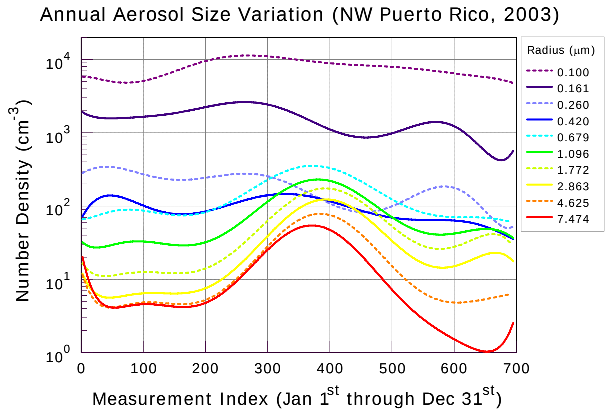

Figure 3 Annual variation of the number density as a function of aerosol particle size measured in Puerto Rico

The RAMS version used in this research contains a new cloud microphysics module described by Saleeby and Cotton (2004), a development from the current microphysics package (Meyers et al. 1997, Walko et al. 1995). The two major differences of this new RAMS cloud microphysics module are the activation of cloud condensation nuclei (CCN) and giant CCN (GCCN) through the use of a Lagrangian parcel model that considers ambient cloud conditions for the nucleation of cloud droplets from aerosol, and a new cloud water hydrometeor category. The large-droplet mode was included to represent the dual modes of cloud droplets that often appear in nature (Berry and Reinhardt 1974). This inclusion serves as a middle step in the growth of cloud droplets. Currently, cloud drops do not grow from 2 to 40 μm in diameter, and then jump to the next hydrometeor category (rain) that is considerably larger, but instead there is another cloud droplet (from 40 to 80 μm in diameter) category that allows a slower drop growth.

Another inclusion is that RAMS now has the option for one- and two-moment prediction for both cloud categories. If both cloud categories are predicted with two moments, and CCN/GCCN are activated, the user may specify the nuclei concentration (cm-3) and the distribution median radius (rg), possible specifications of these parameters now include a domain-wide homogeneous field (used in this research), a horizontally homogeneous vertical profile, and a 3-D variable field. The user also specifies the shape parameter of the hydrometeor gamma distributions. From this information, the CCN/GCCN masses are calculated from lookup tables. These lookup tables are essentially lognormal distributions of CCN/GCCN. Each table delineates between CCN and GCCN and contains 200 mass bins (from 10-19 to 10-8 g for CCN, and from 10-14 to 10-5 g for GCCN) and 14 possible median radii (from 0.01 to 0.96 μm for CCN, and from 1.5 to 5.5 μm for GCCN). Each distribution initially divides up the mass of only one CCN or GCCN (cm-3) of a given size. Thus, to obtain the true distribution at a grid point, each bin of a set distribution for one CCN is multiplied by the true number of nuclei that are activated at a given time. The total mass, corresponding to the number of CCN, is determined by summing the mass in each bin of the distribution until this number is reached.

4. SIMULATING A PRECIPITATION EVENT

June 2, 2003 was the day of maximum rainfall recorded during 2003 by the AO Cooperative Station (not shown). The precipitation recorded by the station was exactly 80.85mm of rain for that day. Since all the experiments consists of short runs, nudged by the NCEP fields every 12 hours, no major changes in the simulated synoptic fields were expected. Hence, the results presented and discussed will focus on total precipitation produced by the runs on the cloud microphysics resolving grid, namely Grid 3.

4.1 *Experimental and Model Configuration*

The first set of model experiments consists of several runs constructed around the new set of observations by the AO for the year of 2003 (see Figure3). These were initialized using the AO dataset, and NCEP atmospheric data to drive the model. A large, coarse grid of 20km is included in the configuration, not shown in Figure 1 and named Grid 1, to perform the downscaling of the large-scale 2.5ºx2.5º NCEP data. A period of 7 days, centered on 02 June was first selected to attempt the replication of the precipitation event. The AP concentration information is updated accordingly to the frequency recorded by the AO. A second run was configured for 06 April of 2003 to validate the improvement in the predictions of precipitations.

The methodology of ingesting the AP information is to drive the model with an initial profile, then restarting the model after updating the AP profile at the times available in the dataset provided by the AO team. In order to better separate the different influences on the results of the two model versions available, and the atmospheric particle observations from the Arecibo Observatory, an ensemble of runs is suggested as shown in Table 1. The cloud spectrum previously used in this type of study was obtained from measurements of maritime cumulus clouds in Hawaii (Rogers and Yau, 1996).

Table 1: Ensemble matrix of runs for Experiment 1

Model Version	Microphysics Information	
	Arecibo Observations	Hawaii Cloud Spectrum
RAMS w/CCN/GCCN activation	run1	run2
RAMS 4.3	Na	run3

4.2 *Results*

After performing the simulations in the methodology explained above, the results for total accumulated precipitation were plotted and compared with the observations from the AO weather station. The maximum-recorded precipitation by the station was about 80mm of rain on the date 02 June 2003; the model simulated a total rainfall of approximately 70, 55, and 35mm in the area of study for run1, run2, and run3, respectively.

A time series of the precipitation predicted by the RAMS model shows that this precipitation was accumulated exactly during a five-hour period in the early hours of 02 June. Figure 4 presents such a time series of total simulated rainfall for the location of maximum precipitation for run1, run2, and run3. The new methodology and AP dataset not only produces more liquid precipitation, but also is far more accurate in the prediction when comparing the results with observations. The higher amounts of precipitation and liquid water concentration are because the new AP information contains relatively lower concentrations during the day hours when convection typically occurs in the Puerto Rican coastlines. As will be discussed in the next section with the idealized experiments, unpolluted skies produce more rainwater in the atmosphere. This simple, but very real and detailed, experiment shows that the new microphysical module with CCN/GCCN activation is capable of satisfactorily replicating a single precipitation event when used with the AP data provided by the Arecibo Observatory.

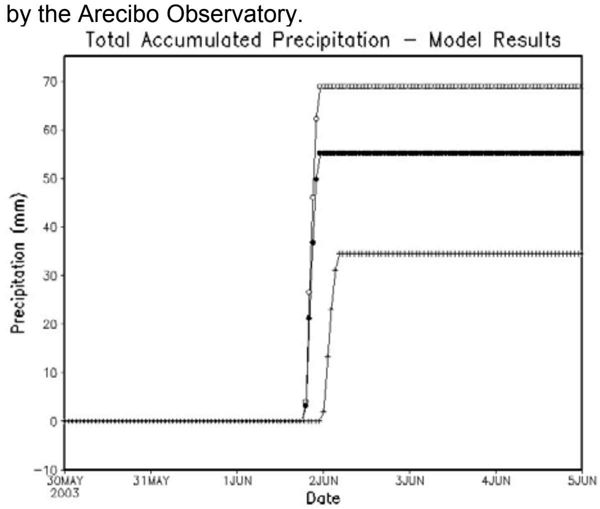

Figure 4 Time series of simulated maximum total precipitation for the simulations run1 (open circles), run2 (close circles), and run3 (crosses)

To demonstrate that the model is indeed capable of reproducing large amounts of precipitation observed over short periods of time with the new microphysics module and the Observatory AP observations, another simulation was set up following the same configuration of run1. The day chosen was 06 April 2003, the second rainiest day of the year in the area of the AO with 68 mm of rainfall recorded. The simulation is identified as run4 and the results for total precipitation accumulated are shown in Figure 5. Here we can see that the model simulated an amount of precipitation almost identical to that recorded by the station, differing only by a few mm of rain, 63mm modeled, demonstrating the model's ability to simulate these shorts events.

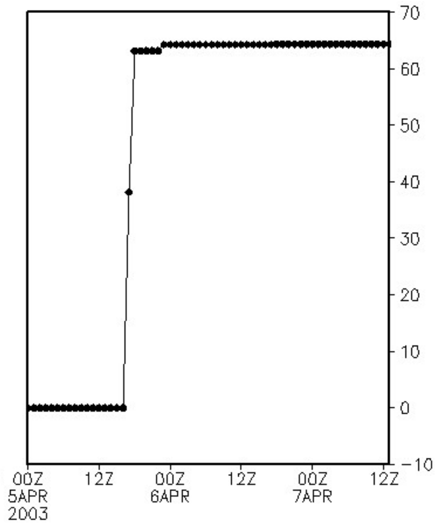

Figure 5 Time series of simulated maximum total precipitation on Grid 3 for the simulation run4 (April 06 2003)

5. SEMI-IDEALIZED RUNS

In order to have a better understanding of the difference in total resolved liquid precipitation between the simulations using the new cloud microphysics module driven with different microphysical information, a second set of experiments were designed to investigate the possible effects of pristine and polluted air on cloud formation and rain development over a limited geographical area.

5.1 *Methodology and Experimental Set-up*

The model runs are constructed and initialized from observations performed by the AO on 26 August 2002 and 27 December 2002 using aerosol data collected using radiometers (Figure 2). The two sets of experiments will be referred to from here on as cld.1 (08/26/2002) and cld.2 (12/27/2002). The model runs are designed to simulate conditions of unpolluted and polluted skies from the data shown in Figure 2, which by itself represents the control run. The experiments were performed with decreased AP concentration and increased concentrations, for the unpolluted and polluted runs respectively (low & high, see Table 2).

The semi-idealized, horizontally homogeneous runs were initialized using sounding data from each of the days when the AP measurements were taken, at the closest time available. The temperature of the lower atmospheric levels was increased by 5 K to stimulate convection, and therefore cloud formation and rainwater development. The different experiments were compared with the control run to study the effect of each one on these parameters. The microphysics moisture complexity was set to the highest level in RAMS. This level incorporates all categories of water in the atmosphere (cloud water, rain water, pristine ice crystals, snow, aggregates, graupel and hail). This parameterization includes the precipitation process. A single grid was used following the same configuration as that of Grid 3 from the previous section. (Figure 1, expanded inset).

Table 2: Ensemble matrix of runs and parameters used for Experiment 2

		cld.1 dN/d(log r/R*) (cm^{-3})-r (μm)	cld.2 dN/d(log r/R*) (cm^{-3})-r (μm)
Low	CCN	10^7-0.5	10^8-0.1
	GCCN	10^6-2	10^7-1
Cntrl	CCN	10^8-0.5	10^9-0.1
	GCCN	10^7-2	10^8-1
High	CCN	10^9-0.5	10^{10}-0.1
	GCCN	10^8-2	10^9-1

where R*=1cm is a characteristic radius.

5.2 *Results*

In this section the results from the different idealized experiments are presented, with special emphasis on the cloud water content (CW), rainwater content (RW), and total liquid water (LW) vertical profiles. The profiles are plotted at the time and location of maximum hydrometeor production of each set of experiments. Figure 6 shows the vertical profiles of CW, RW, and LW for the three simulations of both cld.1 and cld.2.

The cloud water mixing ratio field follows the same pattern in the two experiments. In Figure 6 it is clearly seen that cloud droplet production is significantly larger at low levels (below 1500 m), and at higher levels (between 3 and 4 km) in polluted air than in unpolluted skies, represented by the high and low runs, respectively. However, the rainwater mixing ratio in polluted air is less than a third of that in unpolluted air for the cld.1 runs, and almost non-existent in the cld.2 experiment. A possible explanation for this is, given that droplet production is enhanced in polluted air, the competition for vapor growth will increase resulting in a higher concentration of smaller droplets. Consequently, these droplets do not reach the necessary radius to fall within the cloud, and therefore grow by processes of collision and coalescence. A look at the vertical profiles of cloud droplet number concentration for the cases of polluted and pristine maritime air in experiments cld.1 and cld.2 shows this trend, as depicted in Figure 7. At some heights between the lowest levels and 2500km, the droplet concentration in polluted air was the double than that in unpolluted air for the first set of experiments. Thus, cloud–aerosol interaction impacts crucially the cloud microphysics via the influence on the droplet spectrum width.

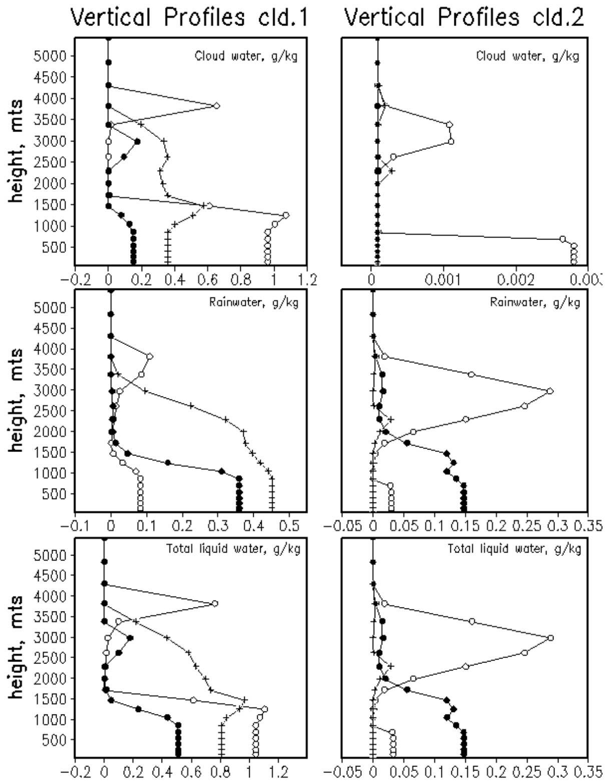

Figure 6 Vertical profiles of cloud water (CW, top panels), rainwater (RW, middle panels), and total liquid water (LW, bottom panels) at the location and time of maximum convection for all experiments. (+) control, (o) high, and (•) low, in both panels

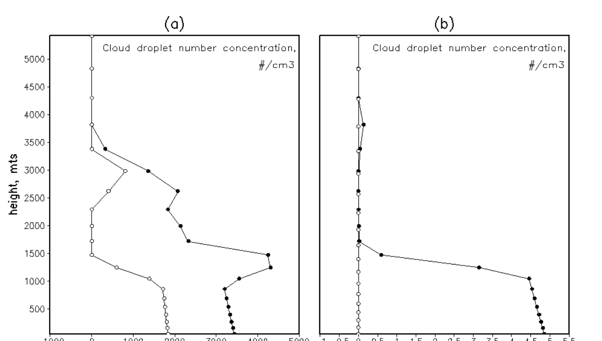

Figure 7 Vertical profiles of cloud droplet number concentration at the location and time of maximum convection for experiments (a) cld.1 and (b) cld.2. In both panel (•) high, and (o) low

5. SUMMARY AND CONCLUSIONS

A new microphysics module incorporated to the Regional Atmospheric Modeling System, and atmospheric particle observations performed at the Arecibo Observatory were used to simulate two short precipitation events, and to investigate the possible effects of AP on cloud formation and rain development. The detailed AP observations are time varying and domain homogeneous. The first experiment showed the model's ability to simulate actual precipitation events recorded over the Observatory area using the recent AP dataset. The second set of idealized runs showed that the cloud water mixing ratio and cloud droplet production is significantly larger in polluted air than in unpolluted skies and that rainwater in polluted air is less than that in unpolluted air (Figures 7-8). This might be due to the possible fact that if a given droplet production is enhanced in polluted air, competition for growth by vapor diffusion among existing droplets will increase, consequently, they will not reach the necessary radius to fall within the cloud, and therefore grow by processes of collision and coalescence. This in turn could explain the fact that run1 predicted more precipitation than run2 and run3 in the actual precipitation event.

The next step in our attempt to produce more accurate and more realistic precipitation predictions using a cloud-resolving mesoscale model is to ingest vertical profiles of atmospheric particle concentrations.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Berry, E. X., and R. L. Reinhardt, 1974: An analysis of cloud drop growth by collection: Part I Double distributions. *J. Atmos. Sci.*, **31**, 1814-1824.

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. Carrio, and J. P. McFadden, 2003: RAMS 2001: Current status and future directions. *Meteor. Atmos. Phys.*, **82**, 5-29.

Dubovik, O., and M. D. King, 2000: A flexible inversion algorithm for retrieval of aerosol optical properties from Sun and sky radiance measurements. *J. Geophys. Res.*, **105**, 20,673-20,696.

Ichoku, C., R. Levy, Y. J. Kaufman, L. A. Remer, R. Li, V. J. Martins, B. N. Holben, N. Abuhassan, I. Slutsker, T. F. Eck, and C. Pietras, 2002: Analysis of the performance characteristics of the five-channel Microtops II Sun photometer for measuring aerosol optical thickness and precipitable water vapor. *J. Geophys. Res.*, **107**, D13, 10.1029/2001JD001302.

Kaufman, Y. J., and T. Nakajima. 1993: Effect of Amazon smoke on cloud microphysics and albedo-analysis from satellite imagery. *J. Applied Meteor.*, **32**, 729–744.

Khain, A., M. Ovtchinnikov, M. Pinsky, A. Pokrovsky, and H. Krugliak, 2000: Notes on the state-of-the-art numerical modeling of cloud microphysics. *Atmospheric Research*, **55**, 159-224.

King, M. D., D, M. Byrne, B. M. Herman, and J. A. Reagan, 1978: Aerosol size distributions obtained by inversion of spectral optical depth measurements. *J. Atmos. Sci.*, **35**, 2153-2167.

Meyers, M. P., R. L. Walko, J. Y. Harrington, and W. R. Cotton, 1997: New RAMS cloud microphysics parameterization. Part II: The two-moment scheme. *Atmospheric Research*, **45**, 3-39.

Pielke, R. A., W. R. Cotton, R. L. Walko, C. J. Tremback, W. A. Lyons, L. D. Grasso, M. E. Nicholls, M. D. Moran, D. A. Wesley, T. J. Lee, and J. H. Copeland, 1992: A comprehensive meteorological modeling system-RAMS. *Meteor. Atmos. Phys.*, **49**, 69-91

Rogers, R. R., and M. K. Yau. 1996: A Short Course in Cloud Physics. Butterwoth-Heinemann, 290 pp.

Saleeby, M. S., 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. Applied Meteor.*, **43**, 182-195.

Walko, R. L., W. R. Cotton, M. P. Meyers, and J. Y. Harrington. 1995: New RAMS cloud microphysics parameterization: Part I: The single-moment scheme. *Atmospheric Research*, **38**, 29-62.