10.3 THE SENSITIVITY OF MODELED SUPERCELL STORM DYNAMICS TO SEVERAL CLOUD MICROPHYSICAL PARAMETERS

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1. INTRODUCTION

Supercell storms are often associated with heavy rain, large hail, strong winds and tornadoes. Predicting such storms and the severe weather associated with them is an important forecasting issue. Producing accurate simulations of the precipitation characteristics of supercell storms has proved challenging to the modeling community. Simulations of classic (CL) supercells appear regularly in the literature, whereas simulations of high-precipitation (HP) and low-precipitation (LP) supercells, where microphysical processes may play a more important role, appear less frequently. Mesoscale numerical models have been successfully used to enhance our understanding of supercell storm dynamics, however, the impact of cloud microphysics on simulated severe storm dynamics has received relatively little attention.

Various microphysical parameterization schemes are currently used in cloud and mesoscale models (e.g. Kessler, 1969; Ferrier, 1993; Walko et al., 1995). Within each of these schemes numerous choices need to be made regarding the representation of microphysical processes. Such choices depend on aspects such as whether the model is to be run in an operational or research mode, what type of system is to be simulated, and what the goal of the simulation is. Computer and time constraints also limit the complexity of the scheme that can be used. For example, a simple single-moment, bulk microphysics scheme is likely to be chosen for operational processes, whereas a more computationally expensive, bin-type representation may be chosen for research purposes. In another example, ice processes are regularly excluded from simulations in which storm dynamics is the focus, even though ice processes may have a significant impact on the thermodynamics of a developing supercell. Such simplifications may certainly be valid, however, we need to understand the implications of these simplifications for severe storm simulations.

Further decisions often need to be made involving specific microphysical parameters. Choosing which microphysical species to represent, determining an appropriate distribution of each species, and assigning a mean diameter for each species are examples of only some of the options that need to be considered when using a single-moment bulk microphysics scheme. Also, parameters may have to be set for a broad range of weather systems when using models in operational mode, where “tweaking” of parameters is not an option.

The influence of microphysical processes on the dynamics of severe storms has been the focus of several numerical simulations and observational studies recently. Jewett et al. (1990) and Johnson et al. (1993) performed numerical simulations to determine the role that ice plays in a highly glaciated supercell storm. They found that the presence of ice had a significant impact on their simulated storms. Their “ice” and “no ice” simulations both generated storms with supercell characteristics, however, these characteristics were better developed and longer-lived in the “ice” simulation.

Tartaglione et al. (1996) reduced the fall velocity of precipitation in the coldest cloud layers to simulate the effects of the presence of ice. They found that this had a strong influence on the storm dynamics, that the transition to the tornadic phase was more pronounced, and that the vertical component of vorticity increased at all levels throughout the storm. Brooks et al. (1994) and Rasmussen and Straka (1998) both highlighted the influence that precipitation distribution within supercells can have on low-level mesocyclogenesis and on storm type classification.

Improving microphysical parameterization schemes in cloud and mesoscale models may be necessary to improve not only our forecasts of supercell precipitation, but also our simulations of storm dynamics. The aim of the research presented here is to investigate the sensitivity of simulated severe thunderstorms to changes in microphysical parameters, in particular, to changes in the mean diameter of rain and hail, to the inclusion of ice species, and to the use of the more sophisticated two-moment microphysical scheme.

2. MODEL SETUP

The mesoscale model used to conduct the sensitivity tests is the Regional Atmospheric Modeling System (RAMS) developed at Colorado State University. A single grid with a grid spacing of 1km and 140 by 170 points in the horizontal was used. The vertical grid spacing is variable and the model top stretches to approximately 23 km. Convection was initiated using a warm (3K perturbation), moist (20% perturbation), 10x10km bubble. The model was homogeneously initialized using a sounding that is characteristic of severe storm days over Oklahoma, with hodograph veering over the lowest 2km AGL. The lower boundary is free-slip. All simulations were run for two hours. Single-moment bulk microphysics (Walko et al., 1995), in which hydrometeor mixing ratios are predicted, was used for most of the results presented here. The bulk microphysical species include vapor, cloud

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droplets, rain, pristine ice, snow, aggregates, graupel and hail, the distributions of which are exponential.

Numerous sensitivity tests were performed in which the mean hail diameter was varied from 3mm to 2cm, and the mean rain diameter from 1mm to 5mm. All other parameters were unchanged. The following four simulations will be examined: (1) using a mean hail diameter of 3mm and a mean rain diameter of 1mm (**SHSR**), (2) using a mean hail diameter of 2cm and a mean rain diameter of 1mm (**LHSR**), (3) using a mean hail diameter of 3mm and a mean rain diameter of 5mm (**SHLR**), and (4) using a mean hail diameter of 2cm and a mean rain diameter of 5mm (**LHLR**). For these acronyms, 'L' and 'S' refer to large and small diameter respectively, and 'H' and 'R' refer to hail and rain respectively. The impact of varying the mean diameter on the hydrometeor size distribution is shown in Figure 1. Increasing the mean hail diameter to 2cm results in a "flatter" distribution in which there are less hydrometeors of smaller sizes compared with the 3mm case. Two other sensitivity simulations were then performed. In the first, all ice species and processes were excluded (NOICE). In the second, the two-moment microphysics scheme (2MOM), in which both the mixing ratio and number concentration are predicted, was used instead of the single-moment scheme.

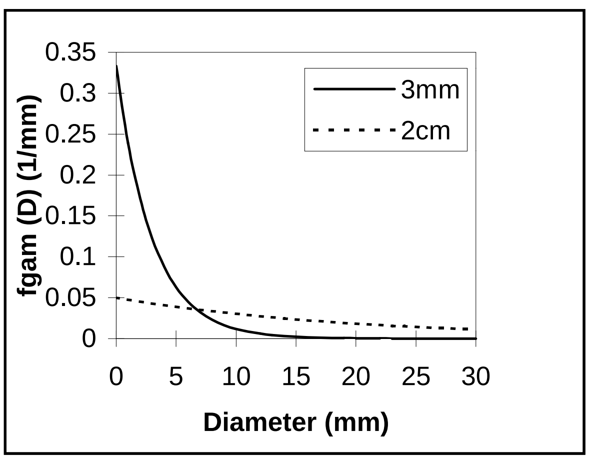

Figure 1: Hydrometeor size distribution for a mean hydrometeor diameter of 3mm and 2cm

3. RESULTS

3.1 Effects of Changing the Mean Diameter

Figure 2 shows the storm tracks of the mean diameter sensitivity simulations. Increasing the mean hail or rain diameter, or both diameters simultaneously, results in a stronger, longer-lived left moving storm (LM) and a slightly slower moving right-moving storm (RM). The LM storms in the larger diameter cases are long-lived in spite of the clockwise turning hodograph, although their RM counterparts are stronger as a result of this clockwise turning, as discussed by Rotunno and Klemp (1982). In the SHSR simulation (Fig. 2a) the RM storm occludes and undergoes the cyclic mesocyclogenesis process observed by Burgess et al. (1982). The LM and RM storms both split again in the LHLR case (Fig. 2d). New convection is seen to develop along the cold air outflow in most of the simulations. Significant differences in the storm development and morphology therefore occur simply as a result of changing the mean hail or rain diameter.

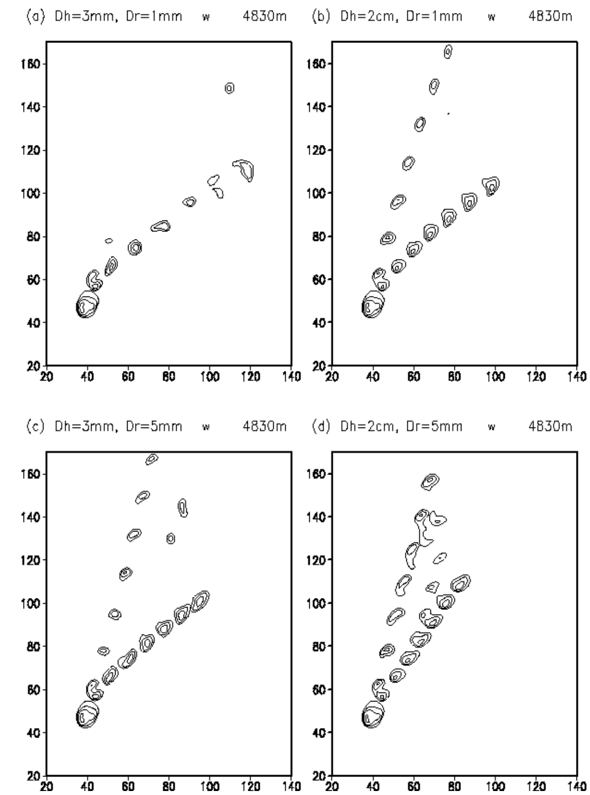

Figure 2: Storm tracks of the (a) SHSR, (b) LHSR, (c) SHLR, and (d) LHLR simulations. Field shown is vertical velocity at 4830m AGL. Contour interval is 10m/s starting with 10m/s. Storm positions are shown at 15 minute intervals starting from the southwest grid corner. Axes are distance (km) from the southwest grid point for all figures. Dh and Dr refer to the mean hail and rain diameters respectively, for all figures.

The cold pool is significantly stronger in the small hail case (SHSR) than in the large hail case (LHSR) (Fig. 3a,b). In the small hail simulation, there are a greater number of smaller stones, and a larger hail surface area is thus exposed. This results in greater melting rates and subsequent evaporation rates, both of which cause the stronger, faster-moving cold pool. Temperatures vary about 12°C across the cold pool in the small hail case (Fig. 3a) while only varying about 4°C in the large hail simulation (Fig. 3b). The cold pool is more extensive in the SHSR simulation as the cooler, denser air expands more rapidly.

The gust front in the SHSR run eventually moves out ahead of the updraft. This movement is enhanced by the rear flank downdraft (RFD). The occlusion and movement of the gust front away from the storm deprives the updraft of moisture and it weakens. A new updraft is seen to develop to the southeast of the original updraft through cyclic mesocyclogenesis (Fig. 2a). The occlusion is not observed in the LHSR simulation. In this simulation, the gust front remains in close proximity to the updraft throughout the entire two hours of simulation resulting in the strong, quasi-steady RM storm (Fig. 2b).

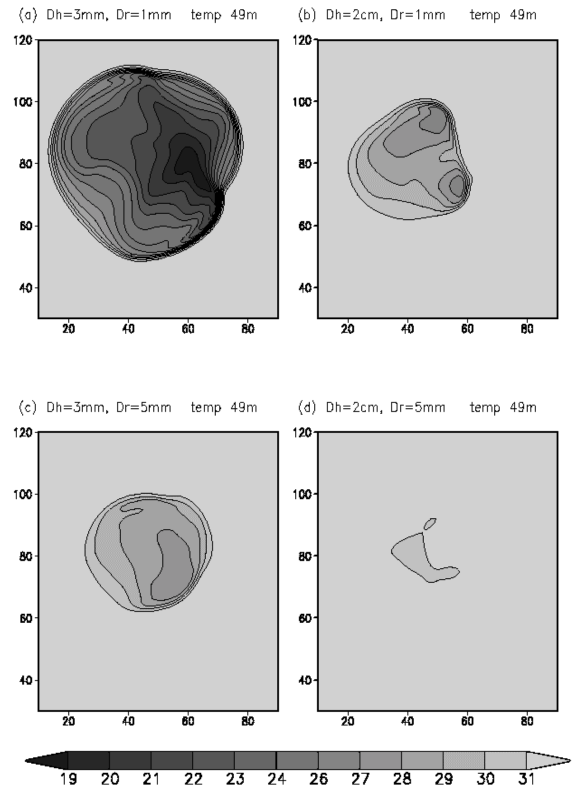

Figure 3: Temperature (C) at 49m AGL after 60 min for the (a) SHSR, (b) LHSR, (c) SHLR and (d) LHLR simulations.

Initial investigation into the longevity of the LM storm reveals the dominance of the buoyant forcing term over the vertical pressure gradient term in the vertical momentum equation. A similar result has been observed by Grasso (2000). In the large hail case (LHSR), the cold pool air that is ingested by the updraft is more positively buoyant than in the small hail case (SHSR), and is thus less detrimental to the updraft. Also, less cold pool air is ingested by the LM updraft in the large hail run compared with the small hail simulation. Changing the mean rain diameter results in similar temperature trends to those observed when changing the mean hail diameter i.e. the greater the mean rain diameter the weaker the cold pool. A very weak cold pool develops when both the rain and hail diameters are large (Fig. 3d).

Changing the mean hydrometeor diameters also affects the precipitation distribution. Reducing the hail size from 2cm (LHSR) to 3mm (SHSR) results in no hail reaching the ground in the latter case (not shown). In the LHSR case, the larger hail can better withstand the effects of melting, allowing some of the hail to reach the ground. Surface rainfall occurs over a much larger area in the SHSR simulation. At higher levels, both hail and rain are closely located to the updraft in the larger hail simulations (Fig. 4b,d). In the smaller hail simulations, hail and rain occur further away from the updraft, and they cover a greater spatial extent (Fig. 4a,c). The smaller hail sizes have smaller fall speeds which allows for their transportation further from the updraft. Larger hail falls closer to the updraft. The rain distribution at these levels appears to be influenced more by the change in hail diameter than in rain diameter. As melting hail is a source of rain in the model, the location of the smaller hail with respect to the updraft will determine, to some degree, the distribution of the rain with respect to the updraft. The surface distribution of the microphysical species can also be attributed to the transportability of the hail species.

Precipitation distribution with respect to the updraft in the large hail cases (Fig. 4b,d) is similar to that found in an HP supercell, while the displacement of the hail and rain further from the updraft in the smaller hail cases (Fig. 4a,c) is more like the distributions found in a CL supercell (Doswell and Burgess, 1993; Rasmussen and Straka, 1998). The precipitation maxima at the surface (not shown) are consistent with these storm types.

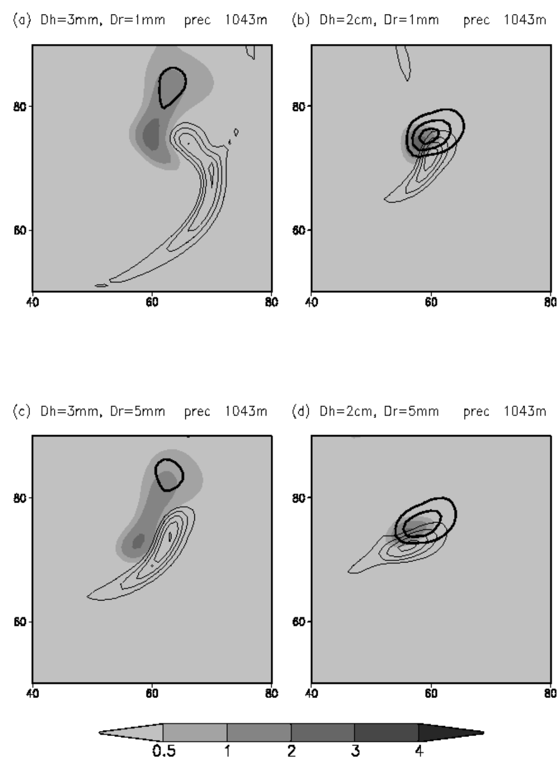

Figure 4: Rain (shaded) and hail (thick dark lines) mixing ratios (g/kg) and vertical velocity (thin lines, 2m/s) at 1043m AGL at 60 min for the (a) SHSR, (b) LHSR, (c) SHLR and (d) LHLR simulations.

The low-level vertical vorticity of the RM storm for each of the diameter sensitivity tests is shown in Figure 5. Decreasing the mean hail diameter from 2cm (LHSR) to 3mm (SHSR) results in a significant increase in the low-level vertical vorticity. Other simulations have been performed using mean hail diameters of 5mm, 1cm and 4cm (not shown) and this trend is consistent. Sensitivity tests have also been performed using straight-line, quarter, half and three-quarter hodographs. An increase in the low-level vertical vorticity with a decrease in mean hail diameter is still observed. This trend may also be seen when decreasing the mean rain diameters (Fig. 5). In the LHLR case, the values do not even approach 0.01 s^{-1}, one of the criterion commonly used for defining a mesocyclone.

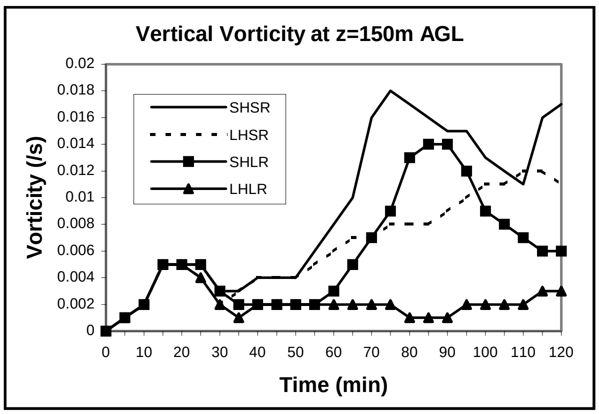

Figure 5: Vertical component of vorticity as a function of time at 150m AGL for the mean diameter simulations

The increase in the low-level vertical vorticity as the mean hail diameter is decreased occurs as a result of baroclinic effects. In the smaller hail cases, the cold pool is stronger and the thermodynamic gradients are greater along the edge of the cold pool. As low-level air approaches the updraft from the northeast, greater horizontal vorticity is generated baroclinically as a result of the stronger thermodynamic gradient along the edge of the cold pool. This horizontal vorticity is then tilted by the updraft and further enhanced by convergence, as seen previously (e.g. Rotunno and Klemp, 1985). The horizontal vorticity vectors and the storm-relative streamlines are almost parallel to the northeast of the updraft. The tilting of this streamwise vorticity results in the cyclonically rotating updraft.

The generation of low-level vertical vorticity lags that of the mid-level vertical vorticity (not shown) in all the diameter sensitivity tests. This has been previously observed (e.g. Rotunno and Klemp, 1985). Variations in the mid-level vertical vorticity magnitudes between the sensitivity tests are not as significant as those at the low levels. However, the mid-level vertical vorticity values are slightly larger for the simulations in which the mean rain diameter is larger. This is still under investigation.

Simply adjusting the mean hail diameter therefore appears to impact numerous aspects of the dynamics and microphysical characteristics of simulated supercell storms. It may also determine the type of supercell storm that develops.

3.3 Effects of Excluding Ice Microphysics

A sensitivity test was conducted in which all ice species and related processes were excluded (Fig. 6). The mean rain diameter was set to 1mm (the default value in RAMS). The NOICE storm tracks and cold pool that develop most closely resemble those of the SHSR simulation. This is somewhat consistent given the mean diameters, however, there are differences. The cold pool is warmer, the LM is longer-lived and the RM storm does not occlude in the NOICE simulation (Fig. 6). The rain is distributed further away from the updraft in the NOICE simulation due to the absence of the faster-falling hail (not shown). The low-level vertical vorticity maximum in the NOICE case is similar to those of the small hail simulations, however, it takes 30 minutes longer to achieve this maximum (not shown). The NOICE simulation results deviate significantly from the larger hail simulations.

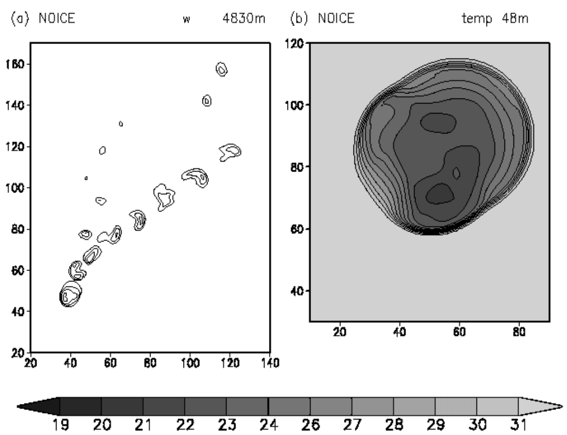

Figure 6: (a) same as Figure 2 for the NOICE simulation and (b) same as Figure 3 for the NOICE simulation.

3.4 Two-Moment Sensitivity Tests

The dynamical and microphysical aspects of the LM and RM storms that develop when using the two-moment scheme are closer to those of the SHSR simulation than the LHSR simulation. The maximum mean hail diameter predicted by the two-moment scheme is 7mm. This occurs in the lower levels of the storm (Figure 7b). A single-moment simulation was performed using a mean hail diameter of 7mm (not shown), the results of which compare relatively well with the 2MOM output. There are, however, subtle, smaller-scale differences and these are currently under investigation.

The two-moment scheme does allow for a better representation of the microphysical characteristics of a storm than the single-moment scheme. For example, the mean hydrometeor diameter may vary throughout the storm when using this scheme. This affects evaporation and melting rates, which in turn has an impact on the cold pool strength and resultant storm dynamics. It is suggested that if a two-moment microphysical scheme cannot be used for all the simulations being conducted, that it be used at least once, particularly if in situ measurements of the cloud microphysical properties are not available. This would provide a basis from which values for microphysical parameters, like the mean hydrometeor diameter, may be determined. While the values obtained from the two-moment scheme are only as good as the scheme itself, it does appear to be an improvement on simply using the default values or guessing at a value.

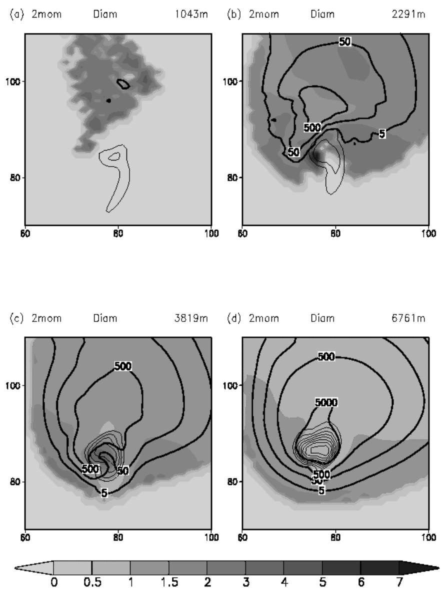

Figure 7: The mean hail diameter (shaded, mm), hail number concentration (thick line, #/m^3) and vertical velocity (thin line, 2m/s in a,b and 5m/s in c,d) at various levels in the storm after 60 minutes for the 2MOM simulation.

4. CONCLUSIONS

Numerical simulations have been performed in which the mean hail and rain diameters were varied, ice processes were excluded, and a two-moment microphysical scheme was employed. The results show that simulated severe storm dynamics and microphysical characteristics are sensitive to all of these changes in the microphysical parameterization scheme, however, changing the mean hydrometeor diameter appears to have the greatest effect. This microphysical parameter is often somewhat arbitrarily selected. In the absence of in-situ measurements, a two-moment microphysical scheme could be used as a basis from which to determine the magnitude of this parameter, and others like it. When ice processes were excluded, the model solution deviated significantly from those simulations in which a mean hail diameter, more in keeping with that predicted by the two-moment scheme (7mm), was used. These results show that changing a single microphysical parameter can significantly alter the dynamics of simulated supercell storms. This points to the need to enhance our understanding of the impact that other such microphysical parameters may have on simulated storm dynamics.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Brooks, H.B., C.A. Doswell III, and R.B. Wilhelmson, 1994: The role of midtropospheric winds in the evolution and maintenance of low-level mesocyclones. *Mon. Wea. Rev*., **122**, 126-136.

Burgess, D.W., V.T. Wood, and R.A. Brown, 1982: Mesocyclone Evolution Statistics. Preprints, *12th Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., 422-424.

Doswell, C.A., and D.W. Burgess, 1993: Tornadoes and tornadic storms: A review of conceptual models. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards, Geophys. Monogr*., Amer. Geophys. Union, 161-172.

Ferrier, B.S., 1993: A double-moment multiple phase four-class bulk ice scheme. Part I: Description. *J. Atmos. Sci*., **51**, 249-280.

Grasso, L.D., 2000: The dissipation of a left-moving cell in a severe storm environment. *Mon. Wea. Rev*., **128**, 2797-2815.

Jewett, B.F., R.B. Wilhelmson, J.M. Straka, and L.J. Wicker, 1990: Impact of ice parameterization on the low-level structure of modeled supercell thunderstorms. Preprints, *16th Conf. on Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 275-280.

Johnson, D.E., P.K. Wang, and J.M. Straka, 1993:Numerical simulations of the 2 August 1981 CCOPE supercell storm with and without ice microphysics.. *J. Appl. Meteor*., **32**, 745-759.

Kessler, E., III, 1969: On the distribution and continuity of water substance in atmospheric circulation. *Meteorol. Monogr*., Am. Met. Soc., 84pp.

Rasmussen, E.N., and J.M. Straka, 1998: Variations in supercell morphology. Part I: Observations of the role of upper-level storm-relative flow. *Mon. Wea. Rev*., **126**, 2406-2421.

Rotunno, R., and J.B. Klemp, 1982: The influence of the shear-induced pressure gradient on thunderstorm motion. *Mon. Wea. Rev*., **110**, 136-151.

Rotunno, R., and J.B. Klemp, 1985: On the rotation and propagation of simulated supercell thunderstorms*. J. Atmos. Sci*., 42, 271-292.

Tartaglione, N., A. Buzzi, and M. Fantini, 1996: Supercell simulations with simple ice parameterization. *Meteor. Atmos. Phys*., **58**, 139-149.

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. *Atmos. Res*., **38**, 29-62.