Generation and Maintenance of Cirrus Clouds by Numerically Modeled Thunderstorms

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Introduction

Thunderstorms represent an important component in the moisture budget of the large-scale atmosphere in the Southern Great Plains, especially in the warm season. In particular, they are a major source of precipitation at the ground and of cloud material in the stratosphere. The former aspect is of significance for the surface energy budget, while the latter impacts the radiation budget.

As such, the moisture budget of individual thunderstorms is of interest. Brooks and Stensrud (1996) reported on the effects of shear and relative humidity (RH) in the troposphere on the moisture budget. They found that while the precipitation efficiency (rainfall out of the storm divided by the input water vapor) declined as shear increased, the amount of cloud water and rainfall produced actually increased with shear. They attributed this to storms in the sheared environments being larger and more organized, so that they ingested more water vapor than storms in unsheared environments. This helps explain an apparent paradox between observational studies (Braham 1952; Foote and Fankhauser 1973; Fankhauser 1988; Heymsfield and Miller 1988) and numerical modeling studies (Weisman and Klemp 1982; Brooks and Wilhelmson 1992). Even though the sheared storms are less efficient, in some sense, the tremendous increase in input water vapor dominates the moisture budget. These results have important implications for convective parameterization schemes which use the precipitation efficiency as a function of the shear alone.

Experimental Design

We used the cloud-scale numerical model of Wicker and Wilhelmson (1995) with a Kessler-type, warm rain, cloud microphysics package with water vapor, cloud water, and rain water. Two sets of thermodynamic profiles have been used in an unsheared environment. The first is an analytic profile based on Weisman and Klemp (1982), with a boundary layer moisture content of 13 g kg^{-1}, yielding a convective available potential energy (CAPE) of about 1500 J kg^{-1}. The RH above 3 km is set at either 10% or 90% (Figure 1). At four levels (4 km, 6 km, 8 km, and 12 km), the RH value switches. As a result, we can consider the effects of small mid- and upper tropospheric layers of dry or moist air. The total mass of the water vapor in the initial conditions varies from 1.5×10^{10} kg to 2.2×10^{10} kg.

The second set of thermodynamic profiles came from soundings taken from the Atmospheric Radiation Measurement (ARM) Program central facility in July 1996. Four cases were used to initialize the model (16 July 2330 UTC, 17 July 0230 UTC, 22 July 2340 UTC, and 25 July 2329 UTC launch times). Slight modification of the thermodynamic profile was required for the latter two days in order to have sustained convection. The 16 and 17 July soundings have much more boundary layer moisture (~16-17 g kg^{-1}) than the analytic soundings, while the 22 and 25 July cases have boundary layer moisture on the order of the analytic conditions. The first two cases are very dry above the boundary layer, close to the 10% RH used in the analytic soundings, while 25 July has a nearly saturated mid- and upper troposphere. The 25 July case also has a much warmer boundary layer, leading to substantially lower RH in the boundary layer.

Results and Discussion

The moisture budget of the modeled storms can be approximated very simply. (For more detail, see Brooks and Wilhelmson 1992.) Water vapor enters the storm, producing cloud water (with zero terminal velocity) when a grid volume becomes saturated. When the cloud water mixing ratio reaches 1 g kg^{-1}, rain water (which has a terminal velocity as a function of the mixing ratio) is produced. Evaporation can take place if the RH of the environment goes below 100%. In short, water vapor entering the storm ends up as cloud water, mostly as anti-level cirrus; rain at the ground; or as water vapor, moistening the atmospheric column. Traditionally, precipitation efficiency (PE) has been defined for cloud

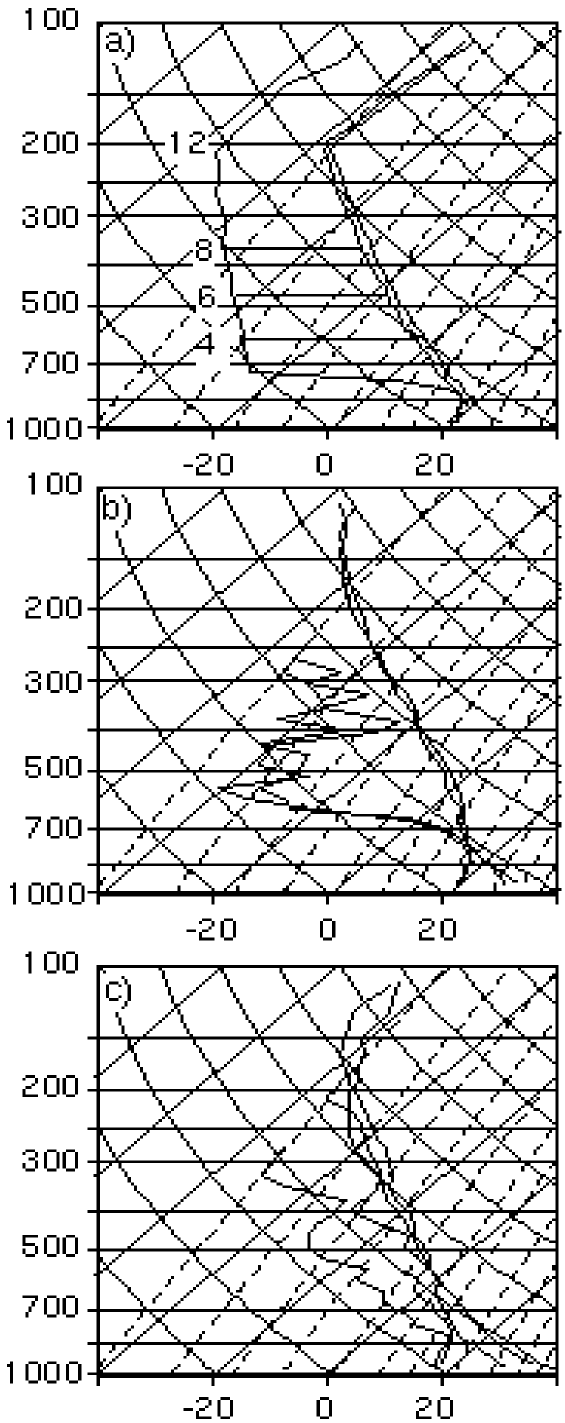

Figure 1. Soundings Used in Simulations. a) Analytic surroundings. Bold line - 10% RH profile and light line - 90% profile. Bold horizontal lines show moisture transitions (see text). Right bold line is temperature. b) Heavy lines-17 July 0230 UTC surrounding, light-16 July 2330 UTC. c) Heavy-22 July 2340 UTC, light-25 July 2329 UTC.

models as the amount of water falling out as rain over the amount of cloud water produced. Results of the experiments are summarized in Table 1. All of the values are through 9000 s, when storms have died out, except for the 17 July case, which creates a strong secondary storm on the outflow from the initial storm after 6000 s. Values from the other storms would not be appreciably changed, but for ease of comparison, the 17 July simulation is truncated at 6000 s. While this results in a slight underestimate of rainfall and vapor production, it is likely to be on the order of a few per cent, based on the behavior of other storms.

The analytic cases illustrate the dramatic impact of humidity just above the boundary layer (~2.5 km) on cloud development. Moistening the entire atmosphere (to 90% RH) above 6 km only increases the cloud production by 2% over a dry atmosphere, while moistening the 4-6 km layer increases it by a further 26%. Moistening all of the atmosphere above the boundary layer raises the cloud production by another 23%.

Moistening the 2.5-6 km layer also has a dramatic impact on rainfall by making it easier in the microphysical package to create rain, associated with large cloud water mixing ratios. The moistening almost doubles the rain that falls out of the storm. Note that it has a small effect on the amount of cloud remaining (~15%), most of which is anvil-level cirrus material.

On a percentage basis, the RH in the 2.5-6 km layer appears to have a greater impact on PE than the layer above that. For those cases with RH of 90% below 6 km, the PE ≈ 44%, while the dry cases have PE ≈ 35%. Although the total mass is lower, as a result of the lower initial production of cloud, a greater percentage of the input water into a storm ends up as cloud (~55% v. ~45%) for the dry mid-tropospheric cases, in comparison to the moist cases.

While interpretation of the analytic cases is relatively straightforward, the observed cases require more care. The 16 July sounding is relatively inefficient at making rain (PE ≈ 24%), but because it produces more than twice the amount of cloud water of any other simulation, it generates more rain and cloud than any other simulation. This result is due to the stronger updraft associated with this storm (peak value of 54 m s^{-1}, while almost all of the others had peaks near 40 m s^{-1}). As a result, it draws dramatically more water into the storm than any of the other simulations. In a manner similar to the sheared storms of Brooks and Stensrud (1996), the 16 July storm is a relatively inefficient producer of rain and of cloud, once water enters the storm. (Note that the small cooling and drying at low levels and warming at mid levels, in the three hours before the 17 July sounding, decrease the intensity of the storm and produce a storm that has a moisture budget

Table 1. Summary of moisture budgets for simulations. Analytic soundings start with an, with first (second) integer indicating relative humidity (either 10% or 90%) of lower (upper) troposphere above boundary layer. Final two digits indicate level of transition in km. 99 indicates constant tropospheric relative humidity cases. Dates for ARM soundings are shown. Next columns are total initial water vapor in domain and amount of cloud produced. Total mass and % of cloud produced summarize fate of cloud produced by model--remaining as cloud (Cloud Rem.), fallen out at ground as rain (Rain), and remaining aloft as water vapor (Vapor). % Rain is approximation to traditional "Precipitation Efficiency." Mass values in 10^9 kg.

			Mass			%		
Case	**Mass initial vapor**	**Mass cloud prod.**	**Cloud rem.**	**Rain**	**Vapor**	**Cloud rem.**	**Rain**	**Vapor**
an1100	150	2.55	1.41	0.90	0.24	55.3	35.2	9.5
an1912	151	2.55	1.41	0.90	0.24	55.3	35.2	9.5
an1908	153	2.57	1.42	0.90	0.25	55.2	35.0	9.8
an1906	160	2.60	1.43	0.90	0.27	55.0	34.8	10.2
an1904	178	3.27	1.71	1.16	0.40	52.2	35.6	12.2
an9104	199	3.06	1.63	1.20	0.23	53.2	39.2	7.6
an9106	218	3.90	1.80	1.70	0.39	46.3	43.6	10.1
an9108	224	4.04	1.79	1.79	0.47	44.2	44.1	11.7
an9112	226	4.05	1.77	1.79	0.49	43.7	44.2	12.1
an9900	227	4.05	1.77	1.79	0.49	43.7	44.2	12.1
25July	180	3.54	1.73	1.74	0.07	48.7	49.3	2.0
17July	220	2.03	1.02	0.92	0.09	50.1	45.4	4.4
16July	229	9.57	5.69	2.28	1.60	59.5	23.8	16.7
22July	238	2.08	1.35	0.68	0.06	64.8	32.5	2.7

much like the moist mid-troposphere analytic cases.) The huge change in the first term of the moisture budget, however, overwhelms the rest of the budget, leading to a fivefold increase in the amount of cloud remaining at the end of the simulation, compared with any of the others. This suggests that some measure of updraft intensity must be included in parameterizations of PE.

The 22 July and 25 July soundings are less efficient at turning input water vapor into cirrus (as approximated by the amount of cloud remaining) than the analytic soundings. Both have low RH in the boundary layer. As a result, the storm has to "work" much harder to saturate the air before clouds can form. The very dry boundary layer on 22 July leads to the evaporation of much of the rain that falls, so that, despite the near saturation of the layer above 4 km, the input water vapor ends up saturating the boundary layer, rather than leading to clouds aloft or rainfall. Thus, despite having the highest absolute humidity, the storm leads to the smallest values of cloud remaining and rainfall.

Small layers of dry (or moist) air have been shown to have dramatic effects on the moisture budget of modeled storms. In addition, the dominant term in the moisture budget of the storms is the initial creation of cloud (equivalent to saturating air). As a result, detailed information on the vertical humidity profile in time and space appears to be necessary to the accurate estimation and prediction of radiative effects due to thunderstorms. The sensitivity of the budget to small changes means that successful parameterization of the effects of convection on the moisture budget, for inclusion in mesoscale or climate models, will be difficult.

References

Braham, R. R., Jr., 1952: The water and energy budgets of the thunderstorm and their relation to thunderstorm development. *J. Meteor.*, **9**, 227-242.

Brooks, H. E., and D. J. Stensrud, 1996: The role of environmental humidity in the moisture budget of thunderstorms. *Proceedings of the Sixth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, March 4-7, 1996, San Antonio, Texas, pp. 31-34. CONF-9603149, U.S. Department of Energy, Washington, D.C.

Brooks, H. E., and R. B. Wilhelmson, 1992: Numerical simulation of a low-precipitation supercell thunderstorm. *Meteorol. Atmos. Phys.*, **49**, 3-17.

Fankhauser, J. C., 1988: Estimates of thunderstorm precipitation efficiency from field measurements in CCOPE. *Mon. Wea. Rev.*, **116**, 663-684.

Foote, G. B. and J. C. Fankhauser, 1973: Airflow and moisture budget beneath a Northeast Colorado hailstorm. *J. Appl. Meteor.*, **12**, 1330-1353.

Heymsfield, A. J., and K. M. Miller, 1988: Water vapor and ice mass transported into the anvils of CCOPE thunderstorms: Comparison with storm influx and rainout. *J. Atmos. Sci.*, **45**, 3501-3514.

Weisman, M. L., and J. B. Klemp, 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. *Mon. Wea. Rev.*, **110**, 504-520.

Wicker, L. J., and R. B. Wilhelmson, 1995: Simulation and analysis of tornado development and decay within a three-dimensional supercell thunderstorm. *J. Atmos. Sci*., **52**, 2675-2703.