The Role of Environmental Humidity in the Moisture Budget of 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 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. Observational studies (Braham 1952; Foote and Fankhauser 1973; Fankhauser 1988; Heymsfield and Miller 1988) have great uncertainty associated with them because of the difficulties of measuring, or even estimating relatively accurately, both the input of water vapor and the output rainfall of a storm. Numerical modeling (Weisman and Klemp 1982; Brooks and Wilhelmson 1992) has addressed the issue as a small part of studies on the behavior of thunderstorms, particularly severe thunderstorms. Here, we consider the moisture budget of "ordinary" thunderstorms in environments with modest potential instability and little or no vertical wind shear. In particular, we focus on the role of environmental humidity above cloud base. The results presented here represent only the beginning of a more complete investigation of the impact of environmental conditions on the moisture budget of thunderstorms.

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. The initial thermodynamic profile is based off of 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 relative humidity above 3 km is set at a constant value for each simulation (Figure 1). That value is varied from 10% to 90%. The total mass of the water vapor in the initial conditions varies from 1.5 x 10^{10} kg to 2.2 x 10^{10} kg.

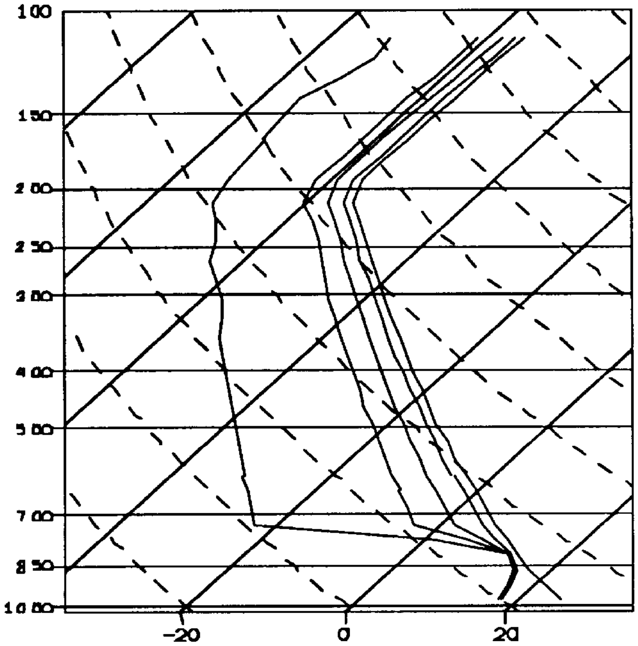

Figure 1. Soundings used to initialize cloud model. Right solid line is temperature. Other solid lines, from right to left, are dewpoint from 90%, 70%, 50%, and 10% relative humidity cases.

We report on three different values of wind shear in the environment. The first is constant wind through the entire depth of the atmosphere. The others have constant shear of 2 x 10^{-3} s^{-} and 4 x 10^{-3} s^{-} from 0-12 km depth, with constant winds above that.

Moisture Budget

For the simple microphysical parameterization, the moisture budget of the numerical model can be described in very simple terms. (A more detailed discussion is given in Brooks and Wilhelmson [1992].) Water vapor enters the storm. If a grid volume becomes saturated, cloud is produced. If the mixing ratio of cloud water exceeds 1 g kg^{-1}, rain water is produced.

If the grid volume becomes unsaturated, cloud and/or rain water can evaporate. (Note that, in the context of the model, the difference between cloud water and rain water is that cloud water does not fall, while rain water does.) Rain water eventually falls out at the ground. Thus, one of three things happens to water vapor that becomes cloud water: 1) it evaporates, becoming water vapor again; 2) remains as cloud water, mostly in anvil material; or 3) falls out of the bottom of the model as rain.

It is important to note that the generation of cloud water by saturation is not particularly dependent on the microphysical parameterization scheme. The transition between water species does depend on the scheme, so that remarks about those steps must be taken with caution, but the initial generation term depends only on the development of saturated air and, as such, is a more "basic" physical process.

An important concept is that of "precipitation efficiency" (PE). PE is the ratio of the amount of rain water falling out of the storm to the water vapor entering the storm. (The values only make sense in terms of integrals over the lifetime of the convective system.) It has been estimated in field observations by using aircraft measurements of the water vapor input term. Foote and Fankhauser (1973) indicated that precipitation efficiency decreases with increasing shear of the environmental wind. This result has been used in the parameterization of rain processes in mesoscale or general circulation models (GCMs). Note that it implicitly assumes that the amount of water vapor entering the storm is directly related to the water vapor in the environment on the scale resolved by the larger-scale numerical models.

In the cloud model, we can investigate all of the stages in the development of rain. In particular, we can define a modified PE as the ratio of the rainfall to the cloud water produced in the model. This is the definition of PE used by Weisman and Klemp (1982). It is equivalent to the "observational" PE if and only if all storms are equally efficient at taking water vapor from the environment into the storm and if the same fraction of water vapor is converted into cloud water. Since it is impossible to define "the storm", we cannot test these two processes independently.

Results and Discussion

With the exception of three simulations (RH = 90%, Shear = 2 x 10^{-3} s^{-}; RH = 90%, Shear = 4 x 10^{-3} s^{-}; RH = 70%, Shear = 4 x 10^{-3} s^{-}), none of the storms show any signs of organization. Those three storms all split and the split storms rotate with the "right" member rotating cyclonically and the "left" member anticyclonically in a process discussed by Weisman and Klemp (1982). The organized nature of the convection helps it persist longer than the disorganized convection. (This result with rotating convection occurring in the high humidity sheared cases is interesting on its on merits, but that is not the focus of the current work.) The other storms with nonzero environmental shear show a tendency to split, but with no organization to the split pairs. As a result, convection is dead in those and the remaining cases by 6000 s. Thus PE has meaning in those cases.

The primary emphases of the results of the moisture budgets are illustrated by looking at measures of the various terms in the budget. Cloud water production is seen to be a strong function of both the relative humidity and the shear (Table 1).

The effect of humidity is to increase the amount of cloud water produced. There are two possible physical effects present here. The first is the simple physical relationship that in the higher RH cases it takes less water vapor coming in from the environment to saturate the air masses. The second is the entrainment of water vapor above cloud base. Heymsfield and Miller (1988) reported that 20% to 30% of the water vapor entering storms came in above cloud base.

The second aspect of the results is that cloud water production increases with shear. This occurs even when there is little organization to the storm, even though the basic physical processes operate that lead to organized storms. North-south cross-sections through the maximum updraft at 2400 s in the 10% RH cases illustrate the different character of the storms with shear (Figure 2). The sheared storms show a slight tendency to split which effectively increases the area from which the storms draw in water vapor. Thus, with shear, the storms draw in more water vapor. Also, the results in Table 1 indicate that the effects of humidity increases with increasing shear. The physical nature of this relationship is unclear

Table 1. Mass (in 10^9 kg) of cloud water produced in simulations through 9000 s.

	Shear		
RH	0	2	4
10	2.53	3.49	5.38
50	2.56	3.88	11.8
70	2.78	5.03	30.2
90	4.05	11.3	88.6

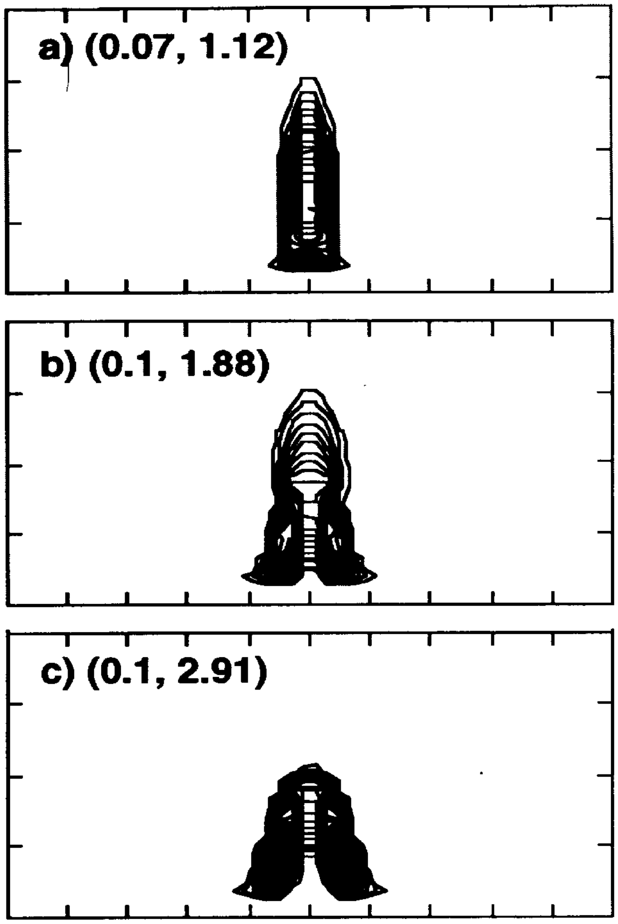

Figure 2. North-south cross-section of cloud water at 2400 s simulation time in portion of domain through maximum updraft. Values in parentheses are (contour interval, maximum value) in g kg^{-1}. Horizontal scale tick marks are 5 km apart and vertical tickmarks are 4 km apart. Each case with relative humidity of 10%. a) Shear=0. b) Shear=0.002 s^{-1}. c) Shear=0.004 s^{-1}. Note that in c), the slope of the updraft is such that in upper levels, the cross-section misses cloud water.

at this time, although it is likely due to the greater organization of the storms. The clearly supercell storms in the highest RH (highest shear environment) produces more than twice as much cloud water as any other of the stimulations. Since the convection in this case is still vigorous at this time, much more cloud would be produced in the storm if the simulation was continued, whereas convection has died out in most of the other simulations.

As mentioned before, PE in numerical models has been defined typically as the ratio of the rainfall to the cloud water produced (e.g., Weisman and Klemp 1982; Brooks and Wilhelmson 1992). For the simulations here, the model PE ranges from near 3% to 12% (Table 2). PE decreases with shear, as reported in the observational studies. In general, PE increases with RH, most likely due to changes in evaporation. Note that the changes in precipitation efficiency are much less than the changes in cloud water production. As a result, the effect on rainfall is quite complicated and, in some of the high shear cases, it actually increases, even though PE decreases (Table 3).

The results of even this simple parameter-range study indicate that the production of rainfall in convection is extremely complex. Thus, its parameterization in GCMs is subject to difficulties. In particular, if one intent of a convective parameterization is to determine what fraction of environmental water vapor in a grid box falls out as rain, interpretation of the observational studies relating shear to PE are difficult. The primary problem is that the observational studies relate the amount of water vapor entering storms to the rain that falls out, while the relationship that is of most interest in GCMs is between the amount of water vapor in the environment and the rainfall. The critical difference between what is in the environment and what enters the storm is a function of both the humidity of the environment and the shear, at the very least. More investigation is necessary in order to develop a

Table 2. Model precipitation efficiency (rainfall divided by cloud water produced) in percent through 9000 s of simulations.

	Shear		
RH	0	2	4
10	11.3	4.8	3.1
50	11.7	5.6	3.9
70	12.4	6.2	6.9
90	12.3	6.2	7.5

Table 3. Mass (in 10^9kg) of rainfall produced in simulations through 9000 s.

	Shear		
RH	0	2	4
10	2.86	1.67	1.68
50	3.00	2.18	4.64
70	3.44	3.14	20.9
90	4.96	7.00	66.8

physically-realistic parameterization of convection that partitions environmental water vapor into cloud and rain water.

At the present time, however, convective parameterization schemes based on a relationship between shear and precipitation efficiency are inadequate and may, in many circumstances, give answers of the wrong sign.

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 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.