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# How does mid-tropospheric dry air affect the evolution of supercellular convection?

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To investigate the influence of mid-tropospheric dry air on the evolution of supercell storms, idealized numerical experiments with several moisture profiles were performed. In an environment with (without) a mid-level dry layer, supercellular convection decays immediately (persists for a long period). A set of trajectory analyses revealed that two suppression processes contribute to the convection decay in the environment with the mid-tropospheric dry layer. One is the entrainment process within the mid-tropospheric dry layer, and the other is the dry-air penetration process. In the latter process, dry air penetrates into the low-level updraft region, so that the supply of warm, moist air for convection is reduced. Neither of the processes contributes effectively in an environment with a dry layer located at a higher altitude. The dependence of the results on the environmental shear profile, evaporation rate, and the amount of convective available potential energy (CAPE) was also examined by additional experiments.



## 1. Introduction

Supercell storms are highly developed single convective clouds, which have a deep, strong, persistent, rotating updraft. They are often accompanied by strong winds, heavy hailfalls, and extremely high lightning flash rates (Markowski and Richardson, 2010). In addition, the vast majority of strong to violent tornadoes are associated with supercell storms (Trapp et al., 2005). Thus, it is important to clarify the conditions that are favorable for the development of supercell storms.

Convective available potential energy (CAPE) and vertical wind shear have been shown to be important in the development of supercell storms. For example, Weisman and Klemp (1982) performed numerical simulations under various conditions and found that environments with large CAPE and strong wind shear were favorable for the development of supercell storms. Their results were consistent with those of Brooks et al. (2003), who examined the relationship between ambient atmospheric states and the severity of supercell storms using reanalysis data. In addition, the behavior of supercell storms has been shown to depend on the shapes of environmental buoyancy and shear profiles (e.g., McCaul and Weisman, 2001; Adlerman and Droegemeier, 2005).

Low-level relative humidity (RH) and convective inhibition (CIN) also affect the development of supercell storms. Brooks et al. (2003) showed that significantly severe storms occur in environments with low lifting condensation levels (LCLs), which correspond to high RH near the surface. Moreover, Grams et al. (2012) examined the difference in environmental parameters between significant tornado events and other severe events using the hourly analysis datasets of the National Centers for Environmental Prediction (NCEP) operational Rapid Update Cycle (RUC) model (Benjamin et al., 2004). They found that environments associated with significant tornadoes exhibit smaller CIN and lower LCL, which correspond to high values of composite parameters such as the significant tornado parameter (STP; Thompson et al., 2003).

An oft-cited previous study, Gilmore and Wicker (1998, hereafter GW98), investigated the influence of mid-tropospheric dry air on the evolution of supercell storms through numerical

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experiments with several base-state moisture profiles. Their results showed that, in environments with dry air aloft, the excessively enhanced low-level outflow cuts off the low-level warm moist inflow, which results in the decay of supercell storms (hereafter, this suppression mechanism is referred to as the GW98 cut-off process). However, their numerical experiments adopted the Kessler warm rain microphysics scheme (Kessler, 1969), which is known to lead to an overestimation of the evaporation rate of rainwater (Gilmore et al., 2004). Therefore, it is necessary to confirm that the GW98 cut-off process will be observed in numerical experiments with a mixed-phase microphysics scheme.

James and Markowski (2010, hereafter JM10) performed numerical experiments similar to GW98 but used a more sophisticated microphysics scheme that includes ice processes. Their results revealed that dry air aloft prevents squall lines and supercellular convection from developing through the entrainment process, especially in a low-CAPE environment. They concluded that the GW98 cut-off process was not observed because the primary mid-tropospheric updraft was not cut off from the boundary between the outflow and warm moist inflow near the surface (i.e., gust fronts), even in the environment with a mid-tropospheric dry layer.

The JM10 study did not refer to the influence of mid-tropospheric dryness on the surface moisture field, which may affect the evolution of supercellular convection. They noted that, in the moist environment, the intensity (amount) of cold pools (potential temperature deficit) was larger than that in the dry environment. However, they did not compare the difference in the moisture field near the surface between the moist and dry environments. Even if potential temperature for a dry parcel is equal to that for a moist parcel, the amount of diabatic heating of the dry parcel during ascending motion, which is associated with its equivalent potential temperature, is smaller than that for the moist parcel. Thus, we focused on the difference in the amount of moisture near the low-level updraft region between environments with and without a mid-tropospheric dry layer. A reduction in the amount of moisture for ascending parcels may influence supercellular convection, thereby acting as another suppression process that differs from both the GW98 cut-off process and the entrainment process.

In this study, to clarify how dry air affects the behavior of supercell storms, numerical experiments with several moisture profiles are performed using a mixed-phase microphysics parameterization. We compare the difference in structures of the simulated supercell storms, particularly with regard to the low-level moisture field. Backward and forward trajectories are calculated to examine the contributions of processes affecting the behavior of supercellular convection. In addition, the sensitivities of the results to the shape of the base-state wind profile and to the evaporation rate of rain water, which influences the intensity of cold pools, are confirmed. Finally, the dependence of the results on the amount of the base-state CAPE is discussed.

This paper is organized as follows. Section 2 describes the model setup, base states, and analysis methods. Section 3 presents the results for each numerical simulation. A conceptual model of the newly proposed suppression process and the results of additional experiments are shown in Section 4. Lastly, Section 5 summarizes the results of the present study.

## 2. Methodology

### 2.1. Numerical model

The Advanced Regional Prediction System (ARPS) version 5.2.12 (Xue et al., 2000), which solves a fully compressible equation system, was used in this study. The domain size was 100 km × 100 km × 20 km. The horizontal grid spacing was 500 m, and the vertical grid interval was extended from 100 m at the ground to 700 m in the upper layer. Open conditions were used on the lateral boundaries. The bottom and top boundaries were rigid walls with a Rayleigh damping layer (the damping coefficient was 0.00333 $s^{-1}$) beginning at 14 km above ground level (AGL). A 1.5-order turbulent kinetic energy closure scheme (Deardorff, 1980) was used for the parameterization of subgrid-scale turbulences. The Weather Research and Forecasting (WRF) single-moment six-class scheme (WSM6; Hong and Lim, 2006), which predicts the mixing ratios of water vapor, cloud water, rain, cloud ice, snow, and graupel, was applied for the microphysics parameterization. The Coriolis force, topography, curvature of the earth, surface friction, and radiation processes were excluded. The integration time was 3 h, and the time steps were 1 s and 3 s for the acoustic mode and other modes, respectively. All prognostic variables were stored on a hard disk every 60 s.

### 2.2. Base states

A composite sounding of the Del City storm that occurred on May 20, 1977 in Oklahoma (Ray et al., 1981), which is one of the most typical supercell storm soundings, was used for the base-state wind and temperature profiles. This sounding has large CAPE and strong veering shear, which promotes the development of deep, right-moving supercellular convection rather than left-moving convection (e.g., Klemp and Wilhelmson, 1978; Klemp, 1987). The storm relative environmental helicity was 101 $m^2 s^{-2}$. An ellipsoidal thermal bubble with maximum amplitude of +2 K was placed at 1.5 km AGL to initiate convection. The diameters of the bubble were 9 km and 1.5 km in the horizontal and vertical, respectively.

Fig. 1b shows the initial RH profiles. For simplicity, we created a modified RH profile in which the original RH value of the Del City sounding was altered to 85% between 0.8 km AGL and 5.8 km AGL (Fig. 1b). This RH profile is referred to as CNTL (black lines in Fig. 1). We also made other moisture profiles in which a mid-level dry layer was located between 1.7 km AGL and 4.2 km AGL. The RH minimum placed at 2.2 km AGL was 40% or 10% (Fig. 1b); sensitivity experiments with these profiles are referred to as DRY40 (red lines in Fig. 1) and DRY10 (blue lines in Fig. 1), respectively.

To examine the dependence of the results on the height of a mid-level dry layer, another RH profile that possesses a mid-level dry layer (RH minimum) between 2.7 km AGL and 5.2 km AGL (at 3.2 km AGL) was produced (Fig. 1b). The RH minimum of this profile was 40%, and the experiment with this profile is referred to as DRY40U (green lines in Fig. 1).

The base-state skew $T$–log $p$ diagrams and profiles for all experiments are shown in Fig. 1a. The surface-based CAPE values for the CNTL, DRY40, DRY10, and DRY40U profiles were 2669 J $kg^{-1}$, 2700 J $kg^{-1}$, 2721 J $kg^{-1}$, and 2692 J $kg^{-1}$, respectively. In all profiles, the mixed-layer LCL was 710 m