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Dependence of the precipitation intensity in mesoscale convective systems to temperature lapse rate

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The dependence of the structure and intensity of precipitation generated within squall lines to environmental temperature lapse rate is investigated by the use of a large set of numerical experiments under idealized model configurations. The lapse rate in a convectively unstable layer is used for the present analysis. The mean precipitation intensity during the simulated period generally increases with the increase in lapse rate, while the maximum precipitation intensity increases with the decrease in lapse rate. The precipitation mean is dependent on the intensity of cold pool resulting from organized convective clouds. In contrast, the precipitation maxima is regulated by relative humidity within the tropospheric lower layer. In an environment with higher lapse rate, a larger amount of CAPE is distributed in a deeper layer of the lower troposphere, which is beneficial for the development and intensification of convection and precipitation. Lapse rate in the troposphere is useful in comparing the characteristics of precipitation produced by mesoscale convective systems that occur in various climate regions of the world and also produced in a future climate under global warming.

1. Introduction

The structure and intensity of mesoscale convective systems (MCSs) are strongly regulated by their environmental conditions such as horizontal wind, temperature, and moisture. These environmental conditions reflect synoptic-scale meteorological phenomena that are characterized by diverse climates ranging from the Tropics, subtropical regions, arid and semi-arid regions, and the midlatitude regions. The intensity of convectively induced precipitation is directly controlled by the structure, organization, and intensity of MCSs and thus can be related to and diagnosed by those environmental conditions. Vertical wind shear determines the structure and organization of MCSs and hence their intensity, while temperature and moisture conditions characterize static stability that would control the development and maintenance of MCSs.

The effects of vertical wind shear on the structure and strength of MCSs have been investigated through observational, modeling, and theoretical studies. It is understood that the dynamical interaction between vertical shear and evaporatively induced cold pool is an important mechanism in controlling the strength and longevity of MCSs, specifically squall lines (Thorpe et al., 1982; Rotunno et al., 1988; Weisman et al., 1988; Fovell and Ogura, 1989; Robe and Emanuel, 2001; Weisman and Rotunno, 2004). Although there is an argument on how the shear affects the MCS structure and intensity (Lafore and Moncrieff, 1989; Rotunno et al., 1990; Weisman and Rotunno, 2004), it is recognized that the interaction between vertical shear and cold pool plays a significant role.

In contrast, there are still unknowns on the effects of temperature and moisture profiles on the structure, evolution, and strength of MCSs. These variables determine the thermodynamic environments that can be diagnosed by various stability parameters and indices (e.g. Bluestein, 1993; Emanuel, 1994). Using the thermodynamic parameters and stability indices, a number of studies examine the thermodynamic environments for MCSs and rainstorms that occur in various climate regions: the United Stated (Bluestein and Jain, 1985; Houze et al., 1990; Cohen et al., 2007); the

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Tropics (Barnes and Sieckman, 1984; LeMone et al., 1998); and the subtropical regions (Wang et al., 1990). However, it is very difficult to determine a universal standard for the diagnosis of the development of MCSs by use of a single stability index or some combination of the indices. This is partly because MCSs develop under various synoptic-scale to micro-scale external forcings. The other reason is that there is a large number of degrees of freedom in determining the profiles of temperature and moisture. For example, even though stability indices are the same among different environments, the shape of the temperature and moisture profiles, which would change the development and organization of MCSs, can be different. In order to understand factors that control the structure and strength of MCSs in various environmental conditions, conducting a systematic set of numerical experiments is a useful tool to examine the sensitivity of MCSs to the temperature and moisture profiles. Considering that the temperature condition largely differs among the various climatological regions, a sensitivity to temperature profile should be clarified.

Recently there are studies that investigate sensitivities to the temperature conditions by carefully setting temperature and moisture profiles. McCaul et al. (2005) examined numerically the sensitivity of supercell storms to environmental temperature by changing only the temperature at the lifting condensation level with convective available potential energy (CAPE) and other environmental parameters being fixed. They found that updraft speed and precipitation efficiency are higher in a colder environment, while the peak precipitation rate in a warmer environment is comparable to that in the colder environment. James et al. (2006) conducted a number of numerical experiments by changing low-level moisture contents and tropospheric temperatures but maintaining CAPE values and showed that in a warmer (colder) environment a weaker (stronger) cold pool is produced and hence the scale of convective cells becomes smaller (larger). Houston and Niyogi (2007) examined how the temperature lapse rate above the level of free convection (LFC) affects the development of cumulus convection by performing numerical experiments and indicated that stronger convection is produced in conditions with a larger temperature lapse rate. Takemi (2007a) investigated numerically the effects of static stability on the squall-line intensity by systematically changing temperature lapse rate with CAPE being unchanged. He showed that a colder environment (which is more unstable) is favorable for generating stronger cold pool, which will highly control the scale and strength of convective updrafts and hence the organization and intensity of squall lines. There is, however, still a remaining issue as to how the characteristics of cloud and precipitation depend on environmental temperature profile.

In the present study, therefore, with the use of the simulated dataset in Takemi (2007a), we examine the structure and intensity of precipitation generated within the squall lines under different temperature conditions. The numerical experiments were conducted in idealized settings in order to focus on the convective dynamics. Squall lines that develop in line-perpendicular, low-level vertical shear are specifically emphasized, since the low-level shear affects most significantly the structure and intensity of squall lines among shears at other height levels (Rotunno et al., 1988; Weisman and Rotunno, 2004). The sensitivity indicated by the numerical experiments is interpreted with the use of a stability parameter. In addition, we discuss the characteristics of precipitation due to convective systems in a future climate with anticipated global warming.

2. Numerical model and experimental design

The numerical model used for the sensitivity experiments is the Advanced Research WRF (Weather Research and Forecasting) model, Version 2.1.2 (Skamarock et al., 2005), which is a non-hydrostatic, compressible atmospheric model developed mainly at National Center for Atmospheric Research in the United States. Although the detailed model setup can be found in Takemi (2007a), it is briefly described here for the readers' convenience.

The WRF model is configured in idealized settings with no Coriolis force, no surface fluxes, no atmospheric radiation, and no horizontal variability in basic states. The physics parameterizations included here are cloud microphysics (Hong and Lim, 2006) and turbulence mixing (Deardorff, 1980). The microphysics parameterization employed here is the most sophisticated single-moment scheme in the WRF version 2.1.2. This scheme solves the prognostic equations for the mixing ratios of water variables, i.e., water vapor, cloud water, rainwater, cloud ice, snow, and graupel, by including the formulations of water/ice conversion processes (Lin et al., 1983) with a revised approach in computing the processes relevant to the formation of cloud ice (Hong et al., 2004). This bulk-type scheme including ice phase is considered to be appropriate to the reproduction of realistic storm behavior in idealized numerical simulations (Fovell and Ogura, 1988). The turbulence mixing scheme, on the other hand, solves a prognostic equation of turbulent kinetic energy to be used for computing the eddy viscosity coefficients both in the horizontal and the vertical directions.

These settings may seem to be too idealized to compare with real cases, but the idealized settings are useful in identifying the essential dynamics of convective processes and have been successfully employed in previous studies (e.g. Rotunno et al., 1988; Weisman et al., 1988; Weisman and Rotunno, 2004). The model domain is 300 km (east–west) by 60 km (north–south) by 17.5 km (vertical) with an open condition at the eastern and western lateral boundaries and the periodic condition at the north and south boundaries. The horizontal grid spacing is 500 m and the vertical grid number is 70.

The model is initialized with horizontally homogeneous states by specifying the vertical profiles of temperature, moisture, and horizontal wind. The temperature and moisture profiles are determined by the use of the analytic function of (Weisman and Klemp, 1982). Environmental potential temperature θ_{env} and relative humidity RH in the troposphere are given as follows:

$$\theta_{env}(z) = \theta_0 + (\theta_{tr} - \theta_0)(z/z_{tr})^{5/4}, \quad (1)$$

and

$$RH(z) = 1 - 0.75(z/z_{tr})^{5/4}, \quad (2)$$