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A sensitivity of squall-line intensity to environmental static stability under various shear and moisture conditions

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Abstract

Squall lines develop in various climate regions having diverse environmental profiles of wind shear, moisture, and temperature. In order to explore the sensitivity of squall lines to these environmental profiles, we have performed an extensive set of numerical simulations under various shear and moisture conditions in midlatitude-continental and tropical–oceanic temperature environments. From the results of the sensitivity simulations and the analyses of the environmental parameters, it is found that the static stability in a convectively unstable layer is of primary importance in determining the strength of squall lines. Under temperature environments having the same static stability, convective available potential energy (CAPE) and precipitable water content (PWC) well describe the squall-line intensity. Vertical shear also plays an important role in determining the squall-line structure as well as the intensity through the interaction with surface cold pool. The combination of the static stability in a convectively unstable layer, CAPE, and PWC should be examined in diagnosing the intensity of squall lines that develop with an optimal shear for their environment.

Keywords: Squall lines; Precipitating cloud systems; Cloud dynamics; Convective instability; Cloud modeling

1. Introduction

Squall lines are one of the significant mesoscale phenomena that locally induce severe winds and high precipitation. Since they develop in various regions of the world, the structure, evolution, and organization of squall lines have a close tie with the dynamic and thermodynamic characters of their environments. Through extensive studies on the dynamics of squall lines in association with environmental vertical wind shear, it has been recognized that the interaction between the low-level ambient shear and the surface cold-air pool of the squall lines is a basic mechanism for the squall-line enhancement and evolution (Rotunno et al., 1988, hereafter RKW; Weisman et al., 1988, hereafter WKR; Fovell and Ogura, 1989; Robe and Emanuel, 2001; Weisman and Rotunno, 2004, hereafter WR04). Takemi (in press), hereafter T06) examined the RKW theory on the interaction mechanism between the ambient shear and the cold pool by performing sensitivity simulations under various environmental moisture conditions and confirmed the validity of the theory over a wide range of moisture conditions.

In addition, the relationship between the thermodynamic environments of squall lines and the squall-line dynamics have also been investigated by a large number

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of observational and numerical studies. In discussing the thermodynamic characters of the squall-line environments, stability indices and parameters and moisture properties are useful parameters (e.g., Bluestein, 1993; Emanuel, 1994). In other words, one of the central arguments on the thermodynamic environments of squall lines is to identify environmental parameters that best describe or diagnose the evolution and strength of squall lines. Therefore, such parameters have been examined for tropical thermodynamic environments (Barnes and Sieckman, 1984; LeMone et al., 1998), for subtropical environments (Wang et al., 1990), and for the midlatitude environments in the United States (Bluestein and Jain, 1985) and in Japan (Chuda and Niino, 2005). However, it is very difficult to diagnose the squall-line characters in terms of a single stability index or a combination of the indices. One of the reasons for this difficulty may lie in the definition of environment itself, since the effects of disturbances cannot be totally eliminated in defining the static environment of squall lines. Furthermore, the shape of temperature and moisture profiles should play a role in the squall-line characters, which will complicate the arguments with stability indices. Numerical experiments therefore are a vital tool for identifying parameters to diagnose the structure and evolution of squall lines.

A number of numerical studies examined the development of convective clouds and storms and mesoscale convective systems under various moisture conditions not only in the planetary boundary layer (Weisman and Klemp, 1982; Takemi and Satomura, 2000) but also in the free troposphere (Gilmore and Wicker, 1998; Lucas et al., 2000; Redelsperger et al., 2002; Ridout, 2002; Takemi et al., 2004). Weisman and Klemp (1982) showed that a nondimensional convective parameter, i.e., bulk Richardson number, delineates various regimes of convective storm structure in a midlatitude environment from their wide range of numerical experiments. T06 investigated the effects of the environmental moisture on the evolution of squall lines under a midlatitude temperature condition by conducting an extensive set of cloud-resolving simulations. Their numerical simulations showed that precipitable water vapor content (PWC) and convective available potential energy (CAPE) regulate the strength and organization of midlatitude squall lines. A remaining issue is then to examine and compare the sensitivities of squall-line structure and intensity to shear and moisture environments in different temperature environments.

As far as supercell storms over the Plains of the United States are concerned, the sensitivity of the storm structure and intensity to environmental temperature profile was examined by McCaul and Weisman (2001), McCaul and Cohen (2002), and McCaul et al. (2005). In interpreting the results of their numerical simulations, they employed CAPE and PWC: these two parameters are popular and useful because they represent the degree of convective instability and tropospheric humidity. Since squall lines are distinct from supercells that have a highly three-dimensional structure and a rotational feature, the response of squall lines to environmental temperature needs to be described. Specifically, the structure and intensity of squall lines under different temperature and moisture conditions should be investigated in association with environmental stability and moisture parameters. This type of sensitivity study would provide an insight into the diagnosis of squall-line potential and also into the parameterization of cumulus effects in global atmospheric models.

The purpose of this paper is, through extending the study of T06, to investigate the sensitivities of the intensity of squall lines to environmental temperature profile under various shear and moisture conditions. We perform a series of cloud-resolving simulations on squall lines that develop in two types of environmental temperature profile: the tropics and the midlatitude environments. In each temperature environment, the impacts of shear and moisture profiles are examined. After describing the squall-line sensitivities from the numerical experiments, we will discuss how the sensitivities can be explained in terms of environmental parameters and thereby present an idea for diagnosing the intensity of squall lines.

2. Numerical model and experimental design

In the present study, we use the Weather Research and Forecasting (WRF) Model (Skamarock et al., 2001), version 1.3, with modifications described in Takemi and Rotunno (2003, 2005). Squall-line simulations are performed for two types of the vertical temperature profile: one is the exactly the same as in T06, i.e., a profile that is typical of midlatitude convective storms (Weisman and Klemp, 1982); and the other is based on the observations over the tropical western Pacific ocean. We hereafter refer to these profiles respectively as the midlatitude and the tropics environment.

The model configuration for the midlatitude environment is exactly the same as in T06. The computational domain is 450 km in the east–west (x) and 160 km in the north–south (y) direction with a 18-km depth. The grid sizes are 1 km in the horizontal directions and 500 m in the vertical direction. In this environment, the vertical grid size of 500 m is considered to be sufficient