A SENSITIVITY OF SQUALL-LINE STRUCTURE AND INTENSITY TO ENVIRONMENTAL STABILITY AND SHEAR

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1. INTRODUCTION

Squall lines are one of the significant mesoscale phenomena that locally induce severe winds and high precipitation, and develop in various climate regions under diverse environmental conditions of wind shear, humidity, and temperature. 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).

In addition, the relationship between the thermodynamic environments and the squall-line dynamics have also been investigated by a large number of observational and numerical studies (Weisman and Klemp 1982, hereafter WK82; Barnes and Sieckman 1984; LeMone et al. 1998; Gilmore and Wicker 1998; McCaul and Weisman 2001; Takemi 2006, hereafter T06). 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 to examine and compare the sensitivities of squall-line structure and intensity to shear and moisture profiles in different temperature environments.

In order to comprehend the structure and evolution of squall lines in various environmental conditions, we investigate the sensitivities of the structure and intensity of squall lines to environmental stability and shear through conducting a series of cloud-resolving simulations with the WRF model.

2. MODEL AND EXPERIMENTAL SETTINGS

We use the WRF model, version 2.1.2, which is configured in an idealized three-dimensional domain having a horizontally uniform reference state. In order to set the vertical profiles of environmental potential temperature $\overline{\theta}$ and relative humidity RH, we employ the analytic function of WK82:

$$\overline{\theta}(z) = \theta_0 + (\theta_{tr} - \theta_0)(z/z_{tr})^{5/4}, \qquad z \le z_{tr} \tag{1}$$

and

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

where $z_{tr} = 12$ km is the tropopause level, θ_{tr} represents potential temperature at the tropopause (WK82 used $\theta_{tr} =$ 343 K), and $\theta_0 = 300$ K the surface potential temperature. By changing the value of θ_{tr}, different temperature environments are defined. Here we examine $\theta_{tr} =$ 343 K, 348 K, 353 K, and 358 K: a smaller (larger) θ_{tr} value represents a midlatitude (tropical) environment. The RH profile is set with (2) except in the lowest layer. The low-level water vapor mixing ratio q_{v0} for control moisture cases is set to 16 $\mathrm{g\,kg^{-1}}$. Table 1 summarizes the CAPE and PWC values for the various θ_{tr} values. The shear profiles examined are westerly shears of 5 and 15 $\mathrm{m\,s^{-1}}$ in the lowest 2.5-km depth, which respectively represents a weak and strong shear environment.

Table 1: q_{v0}, CAPE, CIN, and PWC values for different θ_{tr} values in the control moisture cases.

	q_{v0} (K)	θ_{tr} (g/kg)	CAPE (J/kg)	CIN (J/kg)	PWC (mm/m^2)
CASE01	16	343	3709	21	47.6
CASE02	16	348	2668	25	49.4
CASE03	16	353	1767	31	51.3
CASE04	16	358	1081	38	53.4

The computational domain is 300 km in the east-west (x) and 60 km in the north-south (y) direction with a 17.5-km depth. An open condition is imposed at the east and west boundaries, and a periodic condition at the north and south boundaries. The physics parameterizations employed are only the water and ice microphysics of Lin et al. and the subgrid-scale turbulence mixing that is determined by predicted turbulent kinetic energy. The horizontal grid spacing is 500 m with 70 levels in the vertical. Squall lines are initiated with a y-oriented line thermal that was used in RKW and WKR.

We are specifically interested in the sensitivity of squall-line structure and intensity to environmental temperature profile with a comparable amount of CAPE

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Table 2: Same as Table 1, except for the sensitivity experiments.

	q_{v0} (K)	θ_{tr} (g/kg)	CAPE (J/kg)	CIN (J/kg)	PWC (mm/m^2)
CASE11	13.1	343	1734	62	44.4
CASE12	14.5	348	1772	47	47.9
CASE14	17.7	358	1772	15	54.7

and/or PWC. For example, the environment having moderate CAPE of 1767 $\mathrm{J\,kg^{-1}}$ for the different θ_{tr} values is set by decreasing (increasing) q_{v0} with smaller (larger) θ_{tr}. In this way, sensitivity experiments are performed. Table 2 lists some stability and moisture parameters for the sensitivity experiments with the moderate CAPE.

3. RESULTS

Figures 1 and 2 shows the vertical cross section of the line-averaged structure of the simulated squall lines for the control moisture cases with the weak and strong shear, respectively. Note that no organized structure was found for CASE04 (both shear cases) and the strong shear case in CASE03. The squall-line structure in response to shear intensity is consistent with the studies of RKW and WKR. Comparing the results with the same low-level moisture content, it is seen that larger CAPE environments are favorable for the squall-line development than larger PWC environments.

As a measure of squall-line intensity, the maximum updraft velocity and the area-mean precipitation intensity are examined. The domain for this analysis is focused on eastward-moving systems: the domain at each time is defined as the x coordinate ranging between 20 km ahead of the gust front and 80 km behind the gust front (i.e., an area of 100 km by 60 km). From the time series of the parameters calculated in this analysis domain, the means and standard deviations of these maxima are computed. The time series are examined during the period of 2 to 4 hours at 5-minutes interval.

In Figs. 3 and 4, the means and standard deviations of maximum updraft and area-mean precipitation intensity are shown for the weak and strong shear cases. As shown by T06, the horizontal extent of intense precipitation is well reflected on the mean precipitation intensity. It is clearly demonstrated that both maximum updraft and mean precipitation intensity decrease as CAPE decreases (CASE01 to CASE04) and as θ_{tr} increases (compare CASE03 with CASE11 to CASE14). In spite of comparable CAPE, an environment with smaller CIN (Convective Inhibition) and larger PWC does not produce a stronger system. This unexpected response was not identified in the sensitivity study of T06 which shows that CAPE and PWC well account for the development of squall lines. It is noted that T06 examined the sensitivity in the same temperature environment. The present study reveals a response under different temperature en-

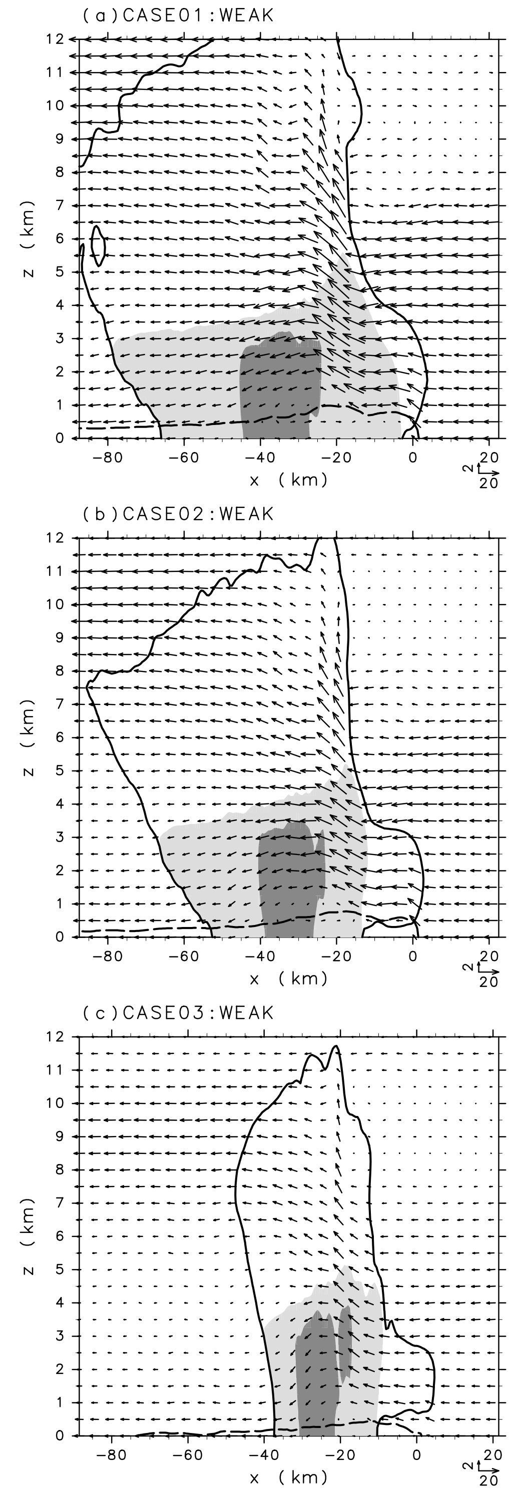

Figure 1: Vertical cross section of line-averaged system-relative wind (vectors), cold-air boundary (dashed line), cloud outline (solid line), and rain fields (shading, mixing ratio of 0.1–1 $\mathrm{g\,kg^{-1}}$ lightly shaded and $> 1\,\mathrm{g\,kg^{-1}}$ darkly shaded) for the weak shear cases.

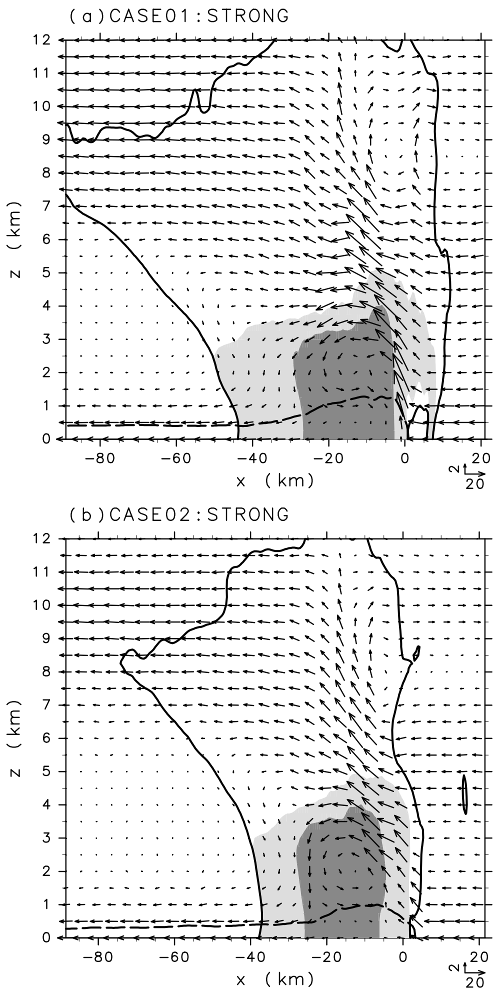

Figure 2: Same as Fig. 1, except for the strong shear cases.

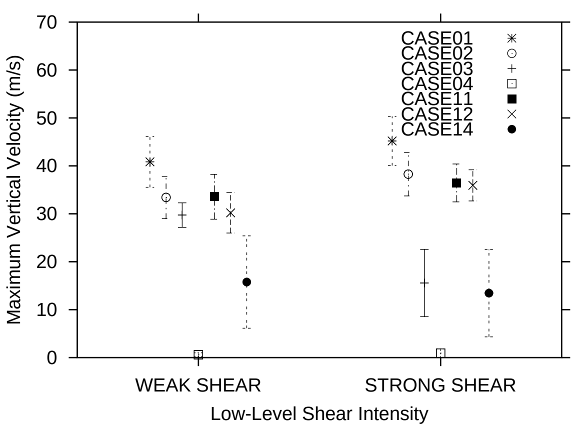

Figure 3: The mean and variability of the maximum updraft velocity in the analysis domain during 2–4 hours for the weak and strong shear cases.

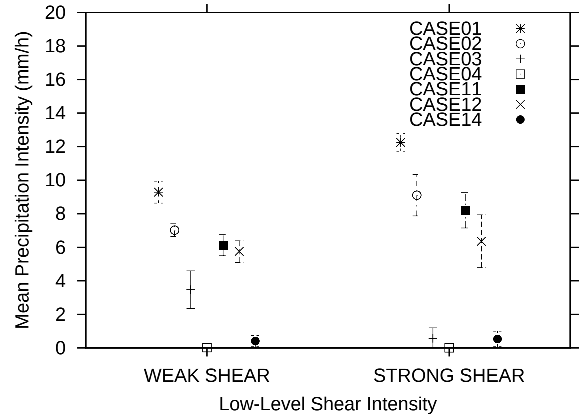

Figure 4: The same as Fig. 3, except for the mean precipitation intensity averaged over the analysis area.

vironments.

A significant difference as revealed in the different temperature environments even with comparable CAPE amounts may be interpreted in terms of environmental stability measures, since the most significant difference is the vertical profile of temperature. There are a number of stability indices for diagnosing thunderstorm potential and intensity. We examine here lifted index and K index (e.g., Bluestein 1993), since lifted index is a measure for a surface-based air parcel and K index depends not only on temperature lapse rate but also on mid-level dryness. In addition, the difference between the ambient low-level maximum equivalent potential temperature (θ_{emax}) and the minimum equivalent potential temperature (θ_{emin}) (which is referred to as $\Delta\theta_e$) is examined, since this parameter is considered to represent the degree of convective instability.

We further examine ambient temperature lapse rates defined as follows:

$$\Gamma_1 = -\frac{T_{\mathrm{LNB}} - T_{\mathrm{LFC}}}{\mathrm{LNB} - \mathrm{LFC}}, \tag{3}$$

$$\Gamma_2 = -\frac{T_{z(\theta_{\mathrm{emin}})} - T_{z(\theta_{\mathrm{emax}})}}{z(\theta_{\mathrm{emin}}) - z(\theta_{\mathrm{emax}})}, \tag{4}$$

where T_{LFC} and T_{LNB} are the temperatures at LFC and LNB, respectively, and $T_{z(\theta_{\mathrm{emax}})}$ and $T_{z(\theta_{\mathrm{emin}})}$ are the temperatures at the levels having θ_{emax} and θ_{emin}, respectively. Thus, the parameter Γ_1 represents the static stability in the whole troposphere, while Γ_2 the static stability in a convectively unstable, lower troposphere. We found that the latter lapse rate, Γ_2, better describes the squall-line intensity.

Table 3 summarizes the environmental stability parameters for the present simulations. In the same temperature environments (CASE01 to CASE04), all the parameters seem to well correspond to the intensity of the simulated squall lines in terms of maximum updraft velocity

Table 3: Environmental stability parameters for the experiments.

	$\Delta\theta_e$	Lifted index	K-index	Γ_2
CASE01	22.8	-9.9	42.1	7.0
CASE02	20.2	-8.2	41.0	6.7
CASE03	17.6	-6.4	40.0	6.4
CASE04	15.0	-4.6	38.9	6.0
CASE11	16.2	-6.3	42.1	6.9
CASE12	16.8	-6.5	41.0	6.7
CASE14	18.8	-6.4	38.9	6.1

and mean precipitation intensity. However, the stability parameters are not always a good measure for diagnosing the intensity of squall lines that develop in different temperature environments (CASE03, CASE11, CASE12, and CASE14). Among the parameters examined, Γ_2, a static stability in a convectively unstable layer, best describes the squall-line intensity under the same CAPE condition.

4. CONCLUSIONS

From an extensive set of numerical experiments, we have examined the sensitivity of the squall-line structure and intensity to temperature, moisture, and shear profiles. It was found that among the cases with the same temperature environment a larger value of CAPE and a larger value of PWC lead to a more enhanced intensity of squall lines. On the other hand, the cases with the different temperature environments indicate an unexpected response of the squall-line intensity to CAPE and PWC values: namely, the simulated squall lines in a warmer environment having CAPE similar to and PWC larger than those in a colder environment are significantly weaker than the colder counterparts. This response to CAPE/PWC values in the different temperature environments is considered to be explained by static stability in a convectively unstable layer. The results showing that squall lines with the warmer temperature profile were significantly weaker than the colder counterparts were clearly delineated in terms of the static stability in the previous subsection: the present warmer temperature profile exhibited a higher stability than the colder profile.

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. The primary role that the static stability plays in controlling the intensity of squall lines is reasonable, because the static stability characterizes the instability of the atmospheric stratification to convective overturning. Under temperature environments having the same static stability, convective available potential energy and precipitable water content well describe the squall-line intensity. Vertical shear plays an important role in determining the squall-line structure as well as the intensity through the interaction with surface cold pool. The present sensitivity analyses therefore present an idea that the combination of static stability (represented by the temperature lapse rate in a convectively unstable layer), buoyancy energy (represented by CAPE), and moisture availability (represented by PWC) can be used for diagnosing the intensity of squall lines that are generated by an optimal shear for the environment.

5. ACKNOWLEDGMENT

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