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THE IMPORTANCE OF MOISTURE PROFILE WITH VERTICAL WIND SHEAR IN THE DYNAMICS OF MID-LATITUDE SQUALL LINES

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1 INTRODUCTION

The dynamics of squall lines has been widely investigated by both observational analyses and numerical simulations by numerous scientists for decades. From the earlier studies, the role of vertical wind shear has been recognized as one of the important ingredients in squall-line dynamics. Numerical modeling studies by Rotunno et al. (1988, hereafter RKW) and Weisman et al. (1988, hereafter WKR) showed that the interaction between low-level vertical wind shear and surface cold-air pool is the primary element in understanding the strength and longevity of squall lines, and stressed that stronger convection develops in a condition in which the dynamical effect of low-level shear and cold pool is optimally balanced. Recent study by Robe and Emanuel (2001) demonstrated that the finding from their squall-line simulations in radiative-convective equilibrium states is in good agreement with the RKW theory. Weisman and Rotunno (2001) and Weisman (2002) performed extensive idealized simulations of squall lines and reconfirmed that the validity of the RKW theory in understanding the dynamics of strong squall lines. In this way, the interaction mechanism between cold pool and vertical shear has been well investigated and seems to be well established.

In contrast to the above issue, the effects of stability and moisture content, which are related to thermodynamics, have not been well investigated. This may be partly because the temperature and moisture profiles vary to a great extent depending on weather conditions and geographical locations and there are a large number of the degree of freedom in setting those profiles. One of the most successful studies in investigating a stability effect is the numerical modeling research by Weisman and Klemp (1982), who showed that the mode of convective storms can be categorized as a multi-cellular or supercelluar type depending on the stability and shear parameter. In their modeling study, a low-level moisture content was changed ranging from 11 through 16 $kg\,kg^{-1}$, and in doing so the effect of buoyancy energy was examined.

In this study, the effects of moisture profile not only in low levels but also in middle levels, coupled with shear intensity and height, on the dynamics of squall lines are investigated using a newly developed cloud model in idealized settings. An extensive set of numerical simulations is performed to investigate the sensitivity of the squall-line morphology and strength to moisture profiles.

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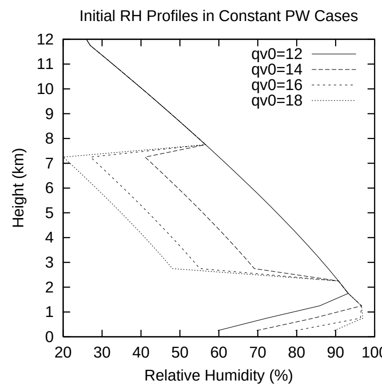

Figure 1: Initial relative humidity profiles in the cases of fixed precipitable water values.

2 MODEL AND EXPERIMENTAL DESIGN

Numerical simulations are performed using the Weather Research and Forecasting (WRF) model (version 1.3) that is currently being developed through collaborative efforts by various U.S. research and operational communities (e.g., Skamarock et al. 2001). The WRF model has various options about numerical schemes for time integration and advection discretization, and the present study employs the third-order Runge-Kutta scheme for the time integration and the third-order upwind scheme for the horizontal and vertical advection terms. The model is run in a three-dimensional domain of 450 km in the x direction and 80 km in the y direction extending from the surface to a height of 18 km. The grid resolution of the simulations is 1 km in the horizontal direction and 500 m in the vertical direction. Open lateral boundary conditions are specified at the x boundaries, and periodic conditions at the y boundaries. The top boundary is rigid lid with an absorbing layer in the upper 6 km depth, while the bottom boundary is free slip. In the

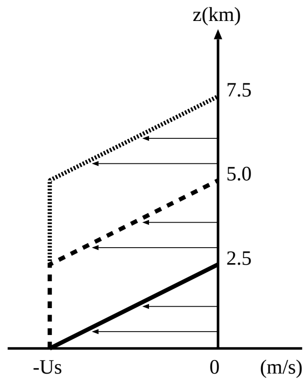

Figure 2: Initial wind profiles.

present idealized simulations, Lin et al. cold rain scheme is used for the parameterization of microphysical processes, and the Coriolis parameter is set to zero. No surface physics and atmospheric radiation parameterizations are included. For the subgrid turbulence parameterization, a 1.5-order scheme using a prognostic equation of turbulent kinetic energy (TKE) is used. The proportionality constant C_k in the eddy viscosity coefficient is adjusted to 0.15, which is 1.5 times larger than the commonly-used value (Takemi and Rotunno 2003). No numerical diffusion is included in the present model.

Squall lines are initiated by a y-oriented line thermal (a 1.5 K-maximum potential temperature excess) of x-radius of 10 km and vertical radius of 1.5 km, placed at the domain center and at a height of 1.5 km. Small random potential temperature perturbations of less than 0.1 K are added to this thermal in order to accelerate the tendency toward three-dimensionality.

A horizontally uniform thermodynamic environment has been created based on the analytic temperature and moisture profile of Weisman and Klemp (1982), which is a typical condition for strong mid-latitude convection. In determining the moisture profile, we set two series of numerical experiments as follows:

1. The water vapor mixing ratio q_{v0} in the boundary layer (i.e., the lowest 1.5 km) is changed from 10 to 18 $\mathrm{kg\,kg^{-1}}$ with 2 $\mathrm{kg\,kg^{-1}}$ interval. The moisture profiles above the boundary layer are the same with each other in spite of the different q_{v0} values. This series is referred to as variable PW.

2. The boundary layer mixing ratio q_{v0} is set to 14, 16, and 18 $\mathrm{kg\,kg^{-1}}$ with the precipitable water (PW) content in each q_{v0} case being held fixed to the value of 42.7 $\mathrm{kg\,m^{-2}}$ (which comes from the case of $q_{v0} = 12$). In this series, the relative humidity in the layer of 2.5-7.5 km is uniformly decreased. The relative humidity profiles in this series of experiments are shown in Fig. 1. This series is referred to as fixed PW.

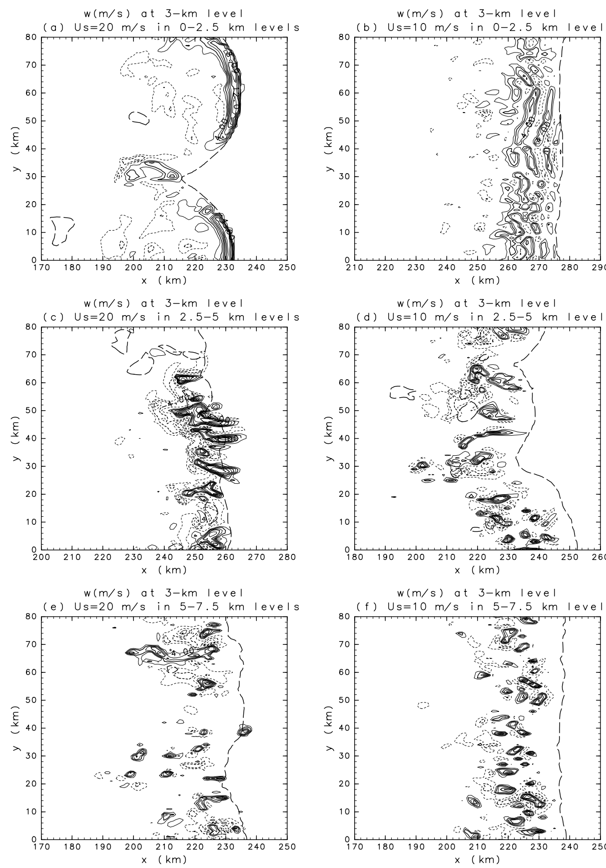

Figure 3: Horizontal cross section of vertical velocity at the height of 3 km, contoured at a 2 $\mathrm{m\,s^{-1}}$ interval at 4 hour in the case of $q_{v0} = 14$ in the variable PW series. The gust front is also indicated by long-dashed lines. A 80 km × 80 km portion of the computational domain is shown.

The temperature profiles in all the cases are the same with that of Weisman and Klemp (1982).

The wind profiles are set as shown in Fig. 2. In our experiments, the depth of the shear layer is fixed to 2.5 km, and the shear layer is gradually elevated from the lowest levels (0-2.5 km) to middle and upper levels (2.5-5 km and 5-7.5 km). The magnitude of wind speed difference in the shear layer, U_s, is set to 0, 10, 15, and 20 $\mathrm{m\,s^{-1}}$. In each q_{v0} case in the variable PW series , ten shear profiles are examined. In the fixed PW series, four shear profiles ($U_s = 10$ and 20 in the layer of 0-2.5 and 2.5-5 km) are examined for each q_{v0} case.

The model is integrated up to six hours, at which time the squall-line cold outflow boundary is still within the computational domain.

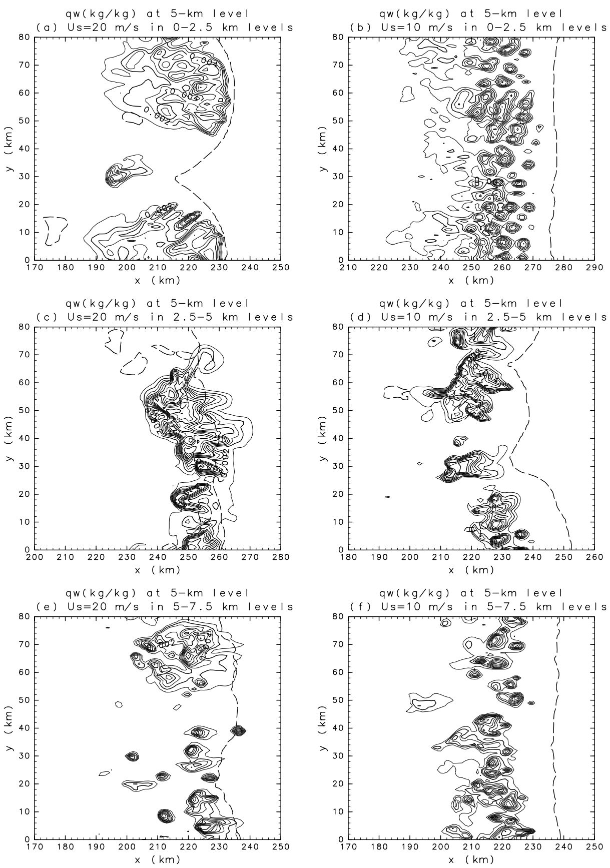

Figure 4: Same as Fig. 3 except for total water condensate mixing ratio at the height of 5 km, contoured at a 0.001 kg kg^{-1} interval.

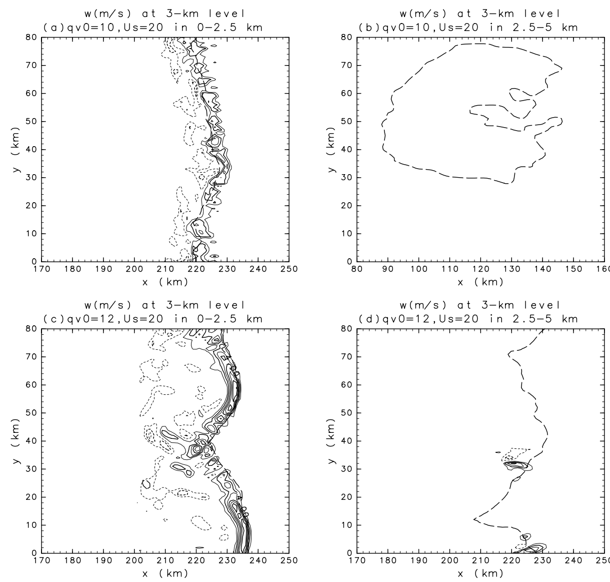

Figure 5: Same as Fig. 3 except for the $q_{v0} = 10$ and 12 cases: (a) $q_{v0} = 10$ and $U_s = 20$ in the 0-2.5 km layer; (b) $q_{v0} = 10$ and $U_s = 10$ in the 2.5-5 km layer; (c) $q_{v0} = 12$ and $U_s = 20$ in the 0-2.5 km layer; (d) $q_{v0} = 12$ and $U_s = 10$ in the 2.5-5 km layer.

3 RESULTS

3.1 Effects of changing low-level moisture content

In this subsection, the results of the experiments in the variable PW series are described.

At first, the results in the $q_{v0} = 14$ case, which RKW and WKR have examined in their squall-line simulations, are demonstrated. Figures 3 and 4 show the horizontal cross sections of vertical velocity and total water condensate, respectively, at the 3-km level around the gust front area for six out of ten shear profiles. Consistent with RKW and WKR, the arc-shaped organization of a squall line can be observed in the strong low-level shear case (Figs. 3a and 4a). As the shear intensity weakens or the height of the shear layer increases, a less organized feature of the simulated squall lines becomes evident (other panels in Figs. 3 and 4).

The remarkable difference between the low-level- and elevated-shear cases, like the one seen in Figs. 3a and 3c, is also examined in other q_{v0} values. Figures 5 and 6 show the horizontal cross section of vertical velocity at the 3-km level for the $q_{v0} = 10$ and 12 cases and the $q_{v0} = 16$ and 18 cases, respectively.

As the boundary layer mixing ratio q_{v0} decreases, linear organization of convection can only be identified in low-level shear cases (Fig. 5), and a stronger shear among the cases we examined here is favorable for the organization (not shown). When the shear layer is elevated from the ground, virtually no cloud development is observed. On the other hand, the moister cases (Fig. 6) show that the cloud development can be seen in both the surface-based and elevated shear cases, although the squall-line structure looks different.

As a measure of the squall-line strength, precipitation intensity averaged over 3-6 hour and over the area between 20 km ahead of the gust front and 80 km behind the front is calculated. Figure 7 summarizes the averaged precipitation intensities obtained in the 10 shear-profile cases in each q_{v0} value. In the drier cases of $q_{v0} = 10$ and 12, shear in the lowest layer is critically important in producing precipitation. In the moister cases of $q_{v0} \geq 14$ with the shear layer being below the 5-km level, shear strength U_s plays a major role in determining the precipitation intensity. On the other hand, a stronger shear in the upper levels of 5-7.5 km has an unfavorable effect on precipitation.

In addition to the surface precipitation, the depth of cold pool head is examined here. Figure 8 shows the depth of cold pool averaged over 3-6 h and the area within 10-km distance behind the gust front. All the q_{v0} cases except the case $q_{v0} = 10$ indicate that the

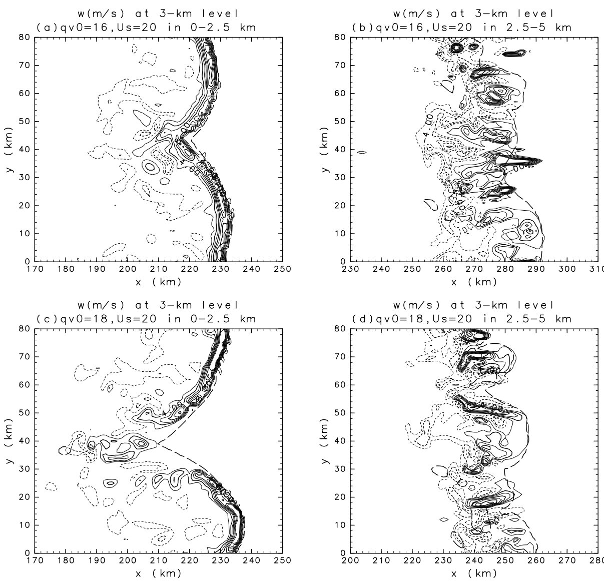

Figure 6: Same as Fig. 3 except for the $q_{v0} = 16$ and 18 cases: (a) $q_{v0} = 16$ and $U_s = 20$ in the 0-2.5 km layer; (b) $q_{v0} = 16$ and $U_s = 10$ in the 2.5-5 km layer; (c) $q_{v0} = 18$ and $U_s = 20$ in the 0-2.5 km layer; (d) $q_{v0} = 18$ and $U_s = 10$ in the 2.5-5 km layer.

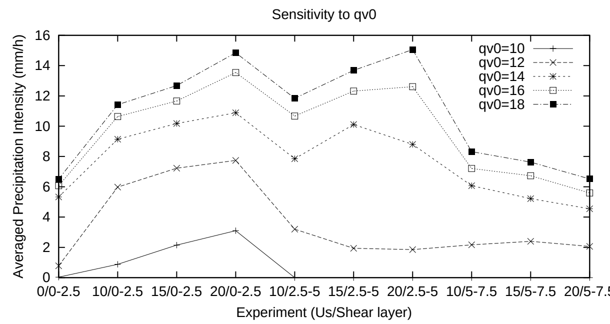

Figure 7: Precipitation intensity averaged over 3-6 h and around the surface gust front in the variable PW series. The digits in the horizontal axis indicate the U_s (in $\mathrm{m\,s^{-1}}$) value and the shear layer levels (in km).

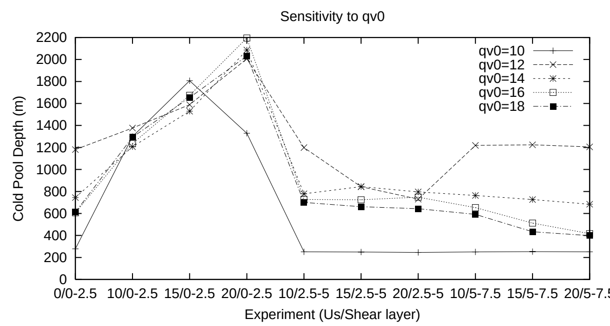

Figure 8: Same as Fig. 7 except for the depth of surface cold pool.

cold pool becomes deeper as the low-level shear becomes stronger. As RKW showed, direct interaction between cold-pool front and low-level shear produces such a deep cold pool. In contrast to the low-level shear cases, the simulated cold pools in the elevated-shear cases are much shallower.

3.2 *Effects of changing low-level and mid-level moisture content*

The organization and structure of the simulated squall lines in the fixed PW series look similar to those in the variable PW series. Figure 9 compares the horizontal cross section of total water mixing ratio at the 5-km level for the cases of $q_{v0} = 18$ in the variable PW and fixed PW sets. General feature of the two cases looks similar to each other, but a close look at the two panels indicates that a smaller-scale feature is more apparent in the fixed PW case. This is because the mid-level relative humidity in the fixed PW series is 40 % drier than that in the variable PW case, and thus dry-air entrainment into the cloud system has a negative influence on the development of convection.

Also in this series of the experiments, averaged precipitation intensity is calculated as a measure of the squall line strength, and is shown in Fig. 10. Comparing Figs. 7 and 10, the increasing tendency of precipitation with the U_s increase can be identified, although the precipitation intensity is slightly smaller in the fixed PW series. From this series of the experiments, it can be said that a moister condition in the boundary layer is more favorable for the squall-line strength than a moister condition above the boundary layer, as long as available column moisture amount (i.e., precipitable water vapor content) is nearly the same.

4 DISCUSSION AND CONCLUSIONS

In order to synthesize the results obtained from all the numerical experiments performed in this study, a single parameter $C/\Delta U$, where C represents a measure of cold pool strength and ΔU denotes a wind speed difference in the shear layer, is examined following the RKW theory. C is defined as follows:

$$C = \sqrt{2 \int_0^H (-B)\, dz}, \qquad (1)$$

where H is the height of the cold pool and B is buoyancy which is defined by virtual potential temperature including the effect of water and ice. RKW theory predicts that $C/\Delta U \sim 1$ is an optimal condition for the development of strong convection.

Figure 11 shows the values of $C/\Delta U$ obtained in the experiments of the variable PW series. The increase in U_s in each shear layer case results in the decrease

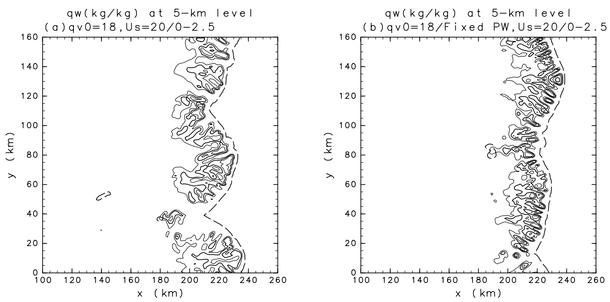

Figure 9: Horizontal cross section of total water condensate mixing ratio at the height of 5 km, contoured at a 0.002 $\mathrm{kg\,kg^{-1}}$ interval in a 160 km $\times$ 160 km portion of the computational area at 4 hour in the cases with $q_{v0} = 18$ and $U_s = 20$ in the lowest 2.5 km: (a) in the variable PW series; (b) in the fixed PW series. The gust front is also indicated by long-dashed lines.

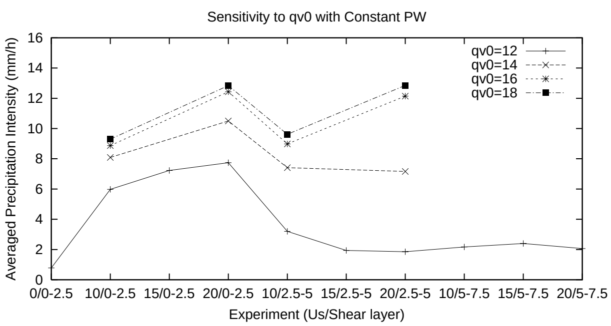

Figure 10: Same as Fig. 7 except for the fixed PW series.

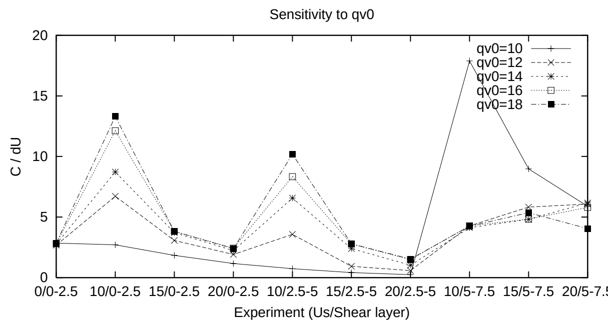

Figure 11: The value of $C/\Delta U$ averaged over 3-6 h.

in $C/\Delta U$. Although the parameter $C/\Delta U$ is generally larger than 1, that parameter seems to well explain the behavior of precipitation intensities shown in Fig. 7. This is also true for the cases of the fixed PW series.

This study can be concluded as follows:

- As the boundary layer becomes drier, the interaction between the squall-line cold pool and low-level ambient shear is more critical to the development of strong convection.
- In moister conditions, stronger shear is favorable for strong convective system in terms of precipitation intensity so long as the shear layer is below 5 km.
- The parameter $C/\Delta U$ from the RKW theory well predicts the strength of squall lines in wide range of moisture conditions.

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REFERENCES

Robe, F. R., and K. A. Emanuel, 2001: The effects of vertical wind shear on radiative-convective equilibrium states. *J. Atmos. Sci.*, **58**, 1427-1445.

Rotunno, R., J. B. Klemp, and M. L. Weisman, 1988: A theory for strong, long-lived squall lines. *J. Atmos. Sci.*, **45**, 463-485.

Skamarock, W. C., J. B. Klemp, and J. Dudhia, 2001: Prototypes for the WRF (Weather Research and Forecasting) model. *Ninth Conf. on Mesoscale Processes*, Fort Lauderdale, FL, Amer. Meteor. Soc., J11-J15.

Takemi, T., and R. Rotunno, 2003: The effects of subgrid model mixing and numerical filtering in simulations of mesoscale cloud systems. *Mon. Wea. Rev.*, **131**, 2085-2101.

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.

Weisman, M. L., and R. Rotunno, 2001: The role of low-level vertical wind shear in promoting strong, long-lived squall lines. Preprints, *Ninth Conf. Mesoscale Processes*, Fort Lauderdale, FL, Amer. Meteor. Soc., 298-302.

Weisman, M. L., 2002: The role of low-level vertical wind shear in promoting long-lived, severe wind-producing convective systems. Preprints, *21st Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., 1-4.

Weisman, M. L., J. B. Klemp, and R. Rotunno, 1988: Structure and evolution of numerically simulated squall lines. *J. Atmos. Sci.*, **45**, 1990-2013.