Impact of Environmental Conditions on the Mesoscale Characteristics of Squall-Line Systems: Toward the Development of Anvil Cirrus Parameterization for General Circulation Models

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Introduction

Our earlier studies (Chin 1994; Chin et al. 1995) indicated that in the mesoscale convective systems (MCSs), a strong coupling exists between deep convection and its related anvil cloud through the interaction among dynamical, thermodynamical and radiative processes. They also showed that the tilting structure of MCSs (sub-GCM-grid feature) makes an important contribution to the water budget of anvil clouds, particularly the tropical anvil due to the jetlike wind profile. However, most earlier general circulation models (GCMs) did not include a direct and physically consistent representation of this coupling. To this end, Randall et al. (1989) suggested a more realistic anvil parameterization by adding prognostic cloud water (or ice) variables to account for the formation of anvil clouds from cumulus detrainment. In addition to this effort, our recent studies further suggest the need to parameterize the tilting structure of MCSs in GCMs.

The objective of this work is to parameterize the large-scale effects of this tilting structure. To this end, we focus on MCSs in an environment with substantial wind shear, such as squall-line systems, since they have longer lifetimes and wider coverage to affect the earth-atmosphere radiation budget and climate. Using varied convective available potential energy (CAPE), wind shear intensity, shear depth, and the pattern of shear profile (i.e., jetlike or non-jetlike wind profile) over a wide range of bulk Richardson number (Ri), a sensitivity study is performed in a cloud resolving model to link its resulting mesoscale ascent/ descent with GCM-resolvable variables. The ultimate goal of this research is to develop an anvil cirrus parameterization (ACP) that will couple with cumulus parameterizations in GCMs to improve the cloud-radiation feedback on large-scale climate.

Model and Initialization

The model used is an extension of Chin and Ogura's (1989) two-dimensional (2-D) cloud model, which is nonhydrostatic and fully compressible. The major improvements include ice microphysics and radiation transfer schemes for longwave (LW) and shortwave (SW). The modified parameterizations of ice microphysics and radiation can simulate mid-latitude and tropical squall-line systems with prominent anvils and realistic mesoscale structures. The radiation schemes used can also distinguish the impacts of hydrometeor phase, size, and shape on cloud optical properties. Refer to Chin (1994) and Chin et al. (1995) for the details of model physics.

Because of the computational constraint for a large number of simulations, radiation is not considered in this sensitivity study. The prestorm conditions of this study are shown in Figure 1, where the bulk Richardson number is chosen between 35 and 240 for multicellular convection (Weisman and Klemp 1984; Fovell and Ogura 1989). The details of these 2-D experiments are listed in Table 1, which contains a total of 36 experiments. The model is initialized by a warm, moist bubble and a horizontally homogeneous sounding.

In addition, a 3-D simulation of the GARP Atlantic Tropical Experiment (GATE) 4 September 1974 squall line was performed in this research (Chin and Wilhelmson 1996). The comparison of this simulation with its 2-D counterpart is used to assess the representative of 2D-based ACP into 3-D applications to GCMs.

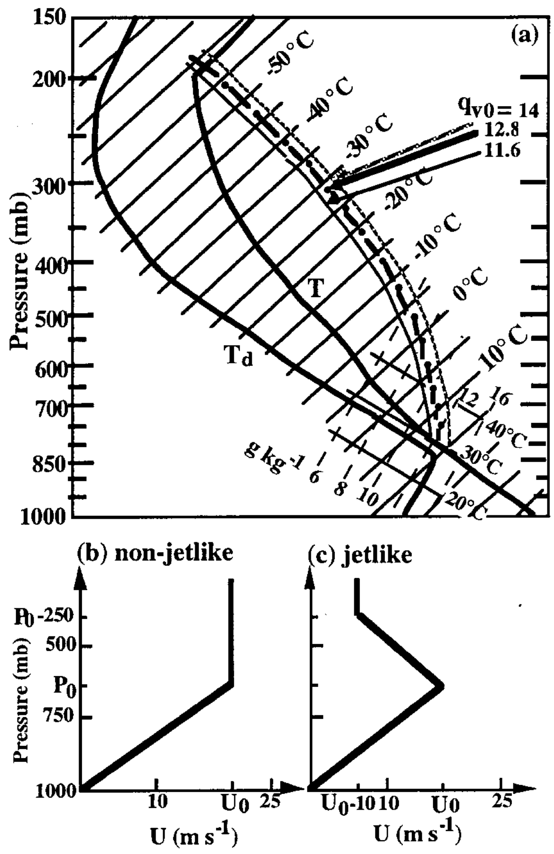

Figure 1. The modified atmospheric composite sounding for the mid-latitude broken-line squall systems. (a) Temperature (T) and dewpoint temperature (T_d) profiles. Moist adiabats with increasing surface mixing ratio (g kg^{-1}) of moisture represent low, medium, and high CAPE, respectively. (b) Non-jetlike wind profile. (c) Jetlike wind profiles. In both (b) and (c), P_0 is set at 750 (500) mb for shallow (deep) shear layer. U_0 ranges from 10 to 25 m s^{-1}.

Results

Two-Dimensional Sensitivity Experiments

These sensitivity experiments are used to study the dependence of mesoscale characteristics of squall-line systems on the convective instability, wind shear intensity, shear layer depth, and the pattern of shear profile. Our results indicate that under constant (medium) CAPE and constant (shallow) shear layer depth of a non-jetlike wind profile, the convective strength of the simulated storm is in positive correlation with the shear intensity, while an opposite relation is found in the stratiform region (see experiments 7, 8, and 9 in Figure 2). With given (medium) CAPE and shear intensity, the deeper shear layer of the non-jetlike wind profile results in stronger convective activity, while it weakens the stratiform region (see experiments 9 and 11 in Figure 2). Further, under constant (medium) CAPE and constant velocity difference (U_0) of the shear layer for the non-jetlike wind profile, the deeper shear layer (i.e., weaker shear) leads to stronger convective updraft, stratiform descent, and weaker stratiform ascent (see experiments 7 and 11 in Figure 2). Similar findings are also seen in each comparison for low and high CAPE, deep shear depth, and the jetlike wind profile, respectively.

The scatter diagram of stratiform ascent and Ri (Figure 3) clearly exhibits a close correlation between maximum stratiform ascent and Ri for any given CAPE, shear depth, and shear profile. Another interesting feature of this scatter diagram is attributed to the prominent separation of two different regimes, which are related to the low and deep shear depth cases. In addition, the stratiform ascent is intensified by the jetlike shear profile and the increasing CAPE; however, these two impacts seem to be weaker than the one caused by the shear depth. All of the aforementioned features related to the stratiform ascent are also seen in its descent counterpart (not shown).

In general, our results indicate that the stratiform (convective) ascent/descent is strengthened (weakened) with the increasing bulk Ri, except the cases involved in varied shear depths.

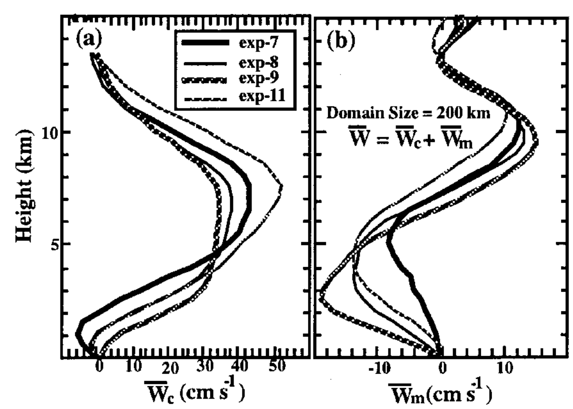

Figure 2. Vertical profiles of domain averaged vertical velocity for experiments 7, 8 , 9, and 11. The averaging domain is selected from the leading edge to the upshear side for 200 km wide. (a) in the convective region. (b) in the stratiform region.

This result suggests that in the ACP, the shallow shear depth case should be treated differently than its deep depth counterpart. As compared to the tropical MCS environment, the deep shear depth is representative of most mid-latitude cases. As a result of the secondary impact of CAPE and shear profile on the stratiform ascent/descent, the upper regime of Figure 3 may represent the general mesoscale characteristics of tropical MCSs, while the lower one fits the mid-latitude cases. However, this suggestion needs more validations for the tropical case before we can generalize the large-scale effects of the sub-GCM-grid process of concern.

Three-Dimensional Simulation and Its Comparison with Two-Dimensional Results

To calibrate our 2-D-based ACP into 3-D applications, we performed a 3-D simulation of the GATE 4 September 1974 squall line (Chin and Wilhelmson 1996). This 3-D simulation replicates many observed features (Houze 1977), such as the arc-shaped rainband structure and its orientation normal to the principal wind shear (Figure 4). The 3-D and 2-D simulations in the multicellular portion of the modeled GATE storm exhibit strong similarity at the dynamical structure, except for the difference at the magnitude (Figure 5). More case studies of 3-D simulations for mid-latitude MCSs are also being undertaken to establish the relationship between 3-D and 2-D simulation as the physical basis for the 3-D applications of the ACP.

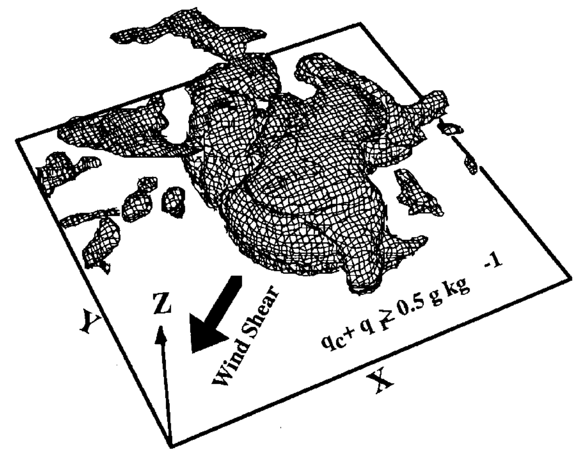

Figure 4. 3-D depiction of the isosurface at 0.5 g kg^{-1} for the total water mixing ratio of the control run at 4 hours of simulation time. The arrow denotes the principal wind shear of environmental winds below 4 km.

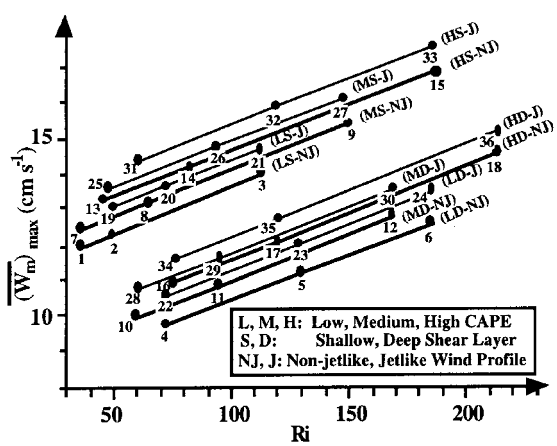

Figure 3. Maximum stratiform ascent strength ($(\overline{W_m})_{max}$) versus the bulk Richardson number (Ri) for varied convective available potential energy, wind shear intensity, shear depth, and shear profile pattern for multicellular storms. The numbers beside the dots represent the experiments, listed in Table 1.

Summary and Discussion

Our results suggest that the bulk Ri is a valuable index for categorizing the mesoscale characteristics of MCSs. Therefore, it might be feasible to parameterize the sub-GCM-grid process associated with the tilting structure of MCS. Because of the computational constraint, we are developing our ACP based on 2-D simulations. Nonetheless, the strong similarity of the resolved mesoscale structure of MCSs between 3-D and 2-D models suggests a promising clue to calibrate the 2D-based ACP into 3-D applications to GCMs.

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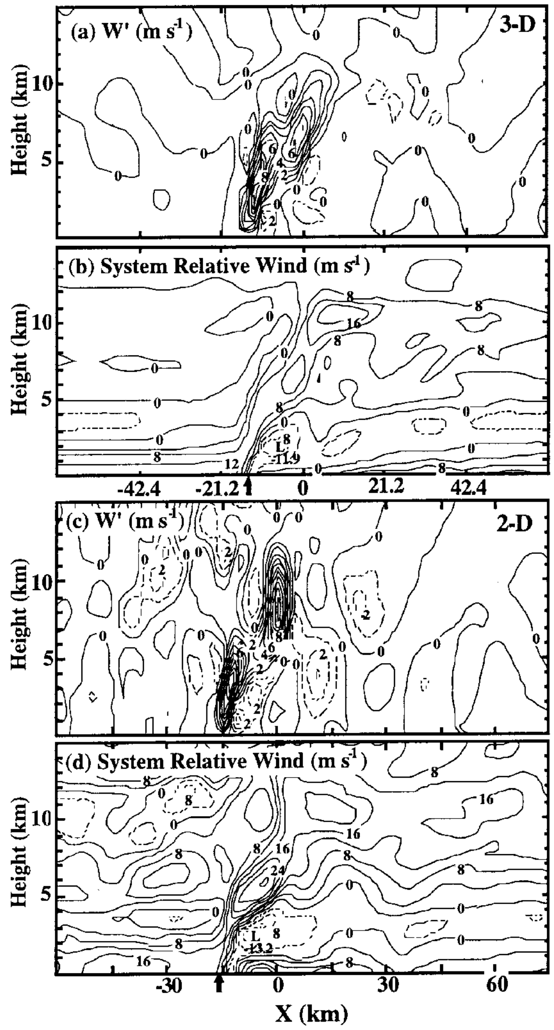

Figure 5. Cross sections in the vertical-horizontal plane of induced vertical velocity and system-relative horizontal velocity in intervals of 1 and 4 m s^{-1}, respectively, at 4 hour of simulation time. (a) and (b) 3-D simulation. (c) and (d) 2-D simulation.

References

Chin, H.-N.S., and Y. Ogura, 1989: Supplementary modeling study of a tropical convective band. *J. Atmos. Sci.*, **46**, 1440-1447.

Chin, H.-N.S., 1994: The impact of the ice phase and radiation on a mid-latitude squall line. *J. Atmos. Sci.*, **51**, 3320-3343.

Chin, H.-N.S., Q. Fu, M.M. Bradley, and C.R. Molenkamp, 1995: Modeling of a tropical squall line in two dimensions and its sensitivity to environmental winds and radiation. *J. Atmos. Sci.*, **52**, 3172-3193.

Chin, H.-N.S., and R.B. Wilhelmson, 1996: Modeling of a tropical squall line in three dimensions: The arc-shaped rainband structure sustained by a supercell-like storm. *J. Atmos. Sci.*, (accepted).

Fovell, R.G., and Y. Ogura, 1989: Numerical simulation of a mid-latitude squall line in two dimensions. *J. Atmos. Sci.*, **46,** 3144-3176.

Houze, R.A., Jr., 1977: Structure and dynamics of a tropical squall-line system. *Mon. Wea. Rev.*, **105**, 1540-1567.

Randall, D.A., Harshvardhan, D.A. Dazlich, and T.G. Corsetti, 1989: Interactions among radiation, convection, and large-scale dynamics in a general circulation model. *J. Atmos. Sci.*, **46**, 1943-1970.

Weisman, M.L., and J.B. Klemp, 1984: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. *Mon. Wea. Rev.*, **110**, 504-520.