Factors Influencing the Parameterization of Anvil Clouds Within General Circulation Models

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Introduction

The overall goal of this project is to improve the representation of clouds and their effects within global climate models (GCMs). We have concentrated on a small portion of the overall goal, the evolution of convectively generated cirrus clouds and their effects on the large-scale environment. Because of the large range of time and length scales involved, we have been using a multi-scale attack. For the early time generation and development of the cirrus anvil, we are using a cloud-scale model with horizontal resolution of 1 to 2 kilometers; for the larger scale transport by the larger scale flow, we are using a mesoscale model with a horizontal resolution of 20 to 60 kilometers. The eventual goal is to use the information obtained from these simulations, together with available observations, to derive improved cloud parameterizations for use in GCMs. This paper presents results from our cloud-scale studies and describes a new tool, a cirrus generator, that we have developed to aid in our mesoscale studies.[a]

Cloud-Scale Study

We chose a midlatitude broken-line squall system for our study because it is the predominant spring time convection in Oklahoma, the location of the first Atmospheric Radiation Measurement (ARM) Program site, and because it can be represented as a two-dimensional system, which is less computationally demanding. To facilitate comparison with published observations, we used a modification of the composite sounding of Bluestein and Jain (1985) to drive our simulations.

The cloud model is an extension of Chin and Ogura's (1989) two-dimensional model, which was used to study a tropical convective rainband. The model is nonhydrostatic and fully compressible; its dynamic framework is similar to that of Klemp and Wilhelmson (1978). Model physics modules include turbulence, a planetary boundary layer (Blackadar 1979), a two-category liquid water scheme (Soong and Ogura 1973), a three-category ice phase scheme (Lin et al. 1983), and long and shortwave radiative transfer (Harshvardhan et al. 1987).

The ice microphysics, which was developed for convective clouds, has been modified to better replicate widely spreading anvil clouds. The Harshvardhan et al. radiative transfer scheme in the cloud and mesoscale models was simplified in the longwave and shortwave calculations by ignoring partial cloudiness and assuming each grid cell was either completely cloudy or clear. The cloud optical properties were also modified to distinguish ice clouds from water clouds using the parameterization schemes of Starr and Cox (1985) and Stephens (1978), respectively. Mixed-phase clouds were also considered in the cloud optical properties. Cloud optical properties are thus functions of model-predicted hydrometeor concentrations.

For this study, we conducted a series of simulations using six different combinations of radiation and microphysics complexity, ranging from no radiation and only liquid microphysics to both longwave and shortwave radiation with full liquid and ice microphysics. To validate our results, we compared the simulations with published observations. The general patterns of the dynamic structure, velocity fields, and pressure deviations bore strong similarities to the features reported by Ogura and Liou (1980) and Smull and Houze (1987). The heating (Q_1) and drying (Q_2)

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profiles were similar to those reported in Ogura and Chen (1977) and Gallus and Johnson (1991). Further, the simulations including both ice and longwave radiation produced a simulated radar reflectivity in which both a melting bright band and a realistic transition zone were present.

Results

An examination of the various runs leads to a number of interesting observations. The first is that the inclusion of ice phase and radiation has very little influence on the thermodynamics of the cloud ensemble, as evidenced by the similarity of their respective Q_1 and Q_2 profiles. On the other hand, a comparison of simulations with and without ice shows that the ice phase has a strong influence on the precipitating water distribution. When ice is present, the dominant total water maximum moves upward. Further, ice doubles the precipitating water mass in the storm and redistributes the precipitating water between the convective and stratiform portion of the storm, as illustrated in Table 1.

When we examined the simulations which included radiation, we found the longwave radiation increases the precipitating water in both the convective and stratified portions of the storms. The addition of shortwave radiation further increases the precipitating water in the ice anvil; however, it reduces the precipitating water in the convective region and in the water anvil.

Table 1. Total precipitating water distribution.

Radiation	None	
Microphysics	Ice-free	Ice
Convective	87.7%	70.25
Stratiform	12.35	29.8%
Total (g/g)	0.667	1.411

We observed that the longwave radiative properties are insensitive to the specific representation of the ice phase. In contrast, the shortwave radiative properties depend strongly upon the condensate phase (Figure 1). The optical depth of the simulated water anvil was 138 compared with 4.4 for the simulated ice anvil that contained approximately the same total precipitable water. In addition, the water anvil had an albedo of between 0.8 and 0.9 (depending upon zenith angle) compared with 0.4 to 0.6 for the ice anvil. The water anvil also had a somewhat larger absorption coefficient. Thus the incident radiation on the surface under the water anvil was 1/10 of that under the ice anvil.

In preparation for developing a GCM parameterization for convectively generated cirrus, we completed a detailed water budget analysis for the mature stage of the storm.

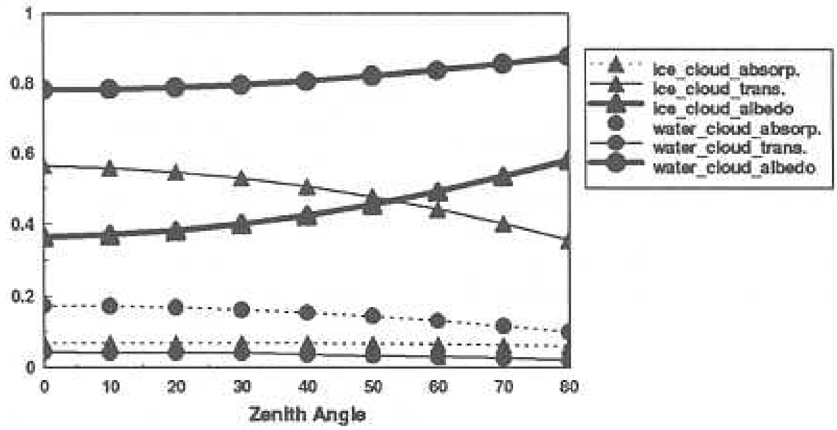

Figure 1. Visible cloud optical properties of temporally and spatially averaged water and ice anvils clouds.

From this analysis, we found that the mechanisms supporting the leading anvil were quite different from those for the larger rear anvil. For the rear anvil, local microphysics, supported by the induced mesoscale circulation resulting from the interaction between hydrometeors and radiation, is an important contributing mechanism. For an all liquid anvil, the local microphysics contribution is nearly the same size as the transport from the convective core. However, for the ice anvil, the transport from the convective core is nearly twice that in the liquid anvil, while the local microphysics contribution remains nearly the same.

Cirrus Generator

We are beginning to study the long-range transport of convectively generated cirrus in a mesoscale model. This model, however, cannot resolve the convective parent that injects ice into the upper levels of the atmosphere, so we must introduce cirrus into the domain in some other manner, e.g., via a convective parameterization, through the initial conditions, or by means of the lateral boundary conditions. We have developed a cirrus generator that is included in the mesoscale model for the purpose of developing cirrus within the model domain.

The cirrus generator is a set of tuned forcing functions that represent the mesoscale forcing caused by the unresolved cumulus clouds. It provides the vertical heating profiles and the momentum, moisture, and heat transport by the unresolved clouds. These profiles are derived by spatially and temporally averaging the collective properties of cloud ensembles from either cloud-scale simulations or observations.

Our initial development has been based upon data from the GARP[a] (GATE) and refined by runs of our cloud scale model. The cirrus generator has been successfully used in a model with 20-km horizontal resolution, producing a reasonable mesoscale cloud structure that reproduced the observed mature stage mesoscale vertical velocity maximum in both magnitude and height and reproduced the observed average surface precipitation rate.

(a) Global Atmospheric Research Program's Atlantic Tropical Experiment

Summary

We have been studying convectively generated cirrus and their effects on the large-scale environment using a midlatitude, broken-line squall system as a test bed. We conducted a series of six simulations using various complexities of radiation and microphysics parameterizations. From these simulations, we found that the inclusion of the ice phase and radiation had little influence on the thermodynamics of the cloud ensemble. However, the inclusion of ice microphysics and longwave radiation significantly increases the water mass and total precipitation in the anvil. We also found that while the longwave radiative properties of the anvil are insensitive to the specific representation of the phase, the shortwave radiative properties depended strongly upon the phase of the condensate. A consequence of this is that by missing the anvil, GCM cumulus parameterization schemes underestimate the cloud albedo and overestimate the surface insolation.

In addition to our cloud-scale studies, we are studying the long-range transport and life cycle of the anvil using a mesoscale model. We have developed a cirrus generator that can be included in a mesoscale model with horizontal resolutions too large to resolve cumulus clouds. The cirrus generator represents the mesoscale forcing caused by the unresolved cumulus clouds and forces cirrus into the mesoscale model, which then interacts with the larger scale flow fields.

In the future, we plan to expand our cloud-scale studies to other convective systems moving initially in tropical Pacific convection. We will begin our mesoscale studies of the life cycle of cirrus anvils using the cirrus generator to develop the cirrus in the mesoscale domain. We will combine the information from our modeling studies with available observations to develop more robust GCM parameterizations of cirrus anvils and their effects on the larger scale flow.

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