RADIATIVELY-INDUCED ANVIL SPREADING
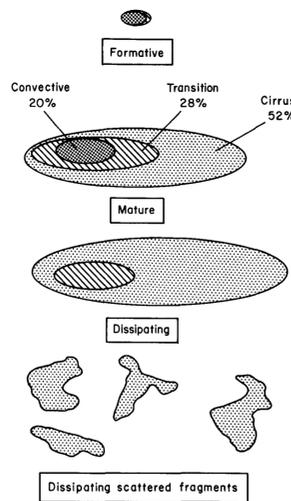
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Introduction

Observations show that cirrus clouds often result from the life cycle of convective cloud systems. Machado and Rossow (1993), using satellite imagery, found that relatively thin high clouds constitute a large part of of the area covered by such systems, especially when considering the system's entire life cycle.

Schematic of the life cycle of a convective system [from Machado and Rossow (1993).]

1-km visible imagery with radar overlay showing anvil formation and spread on 16 July 2002 at half-hourly intervals during CRYSTAL-FACE. (http://angler.larc.nasa.gov/crystal/)

Schematic of Convective System Life Stages
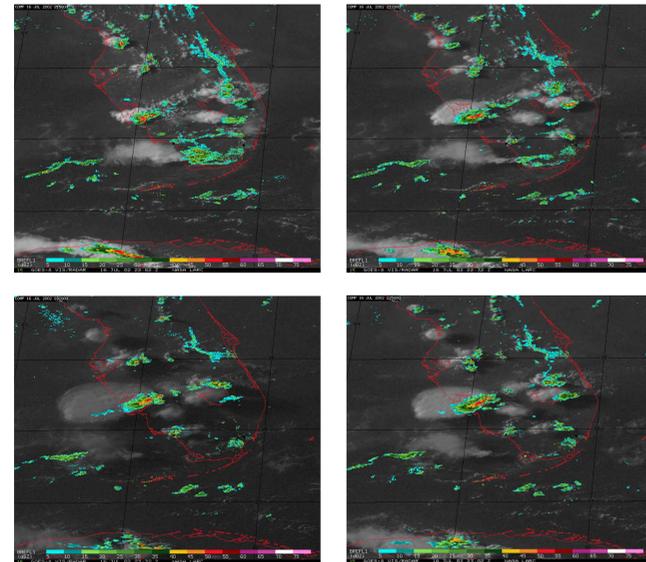
The Problem

The radiative effects of a convectively generated cirrus cloud system depend on the ice mass and its spatial and temporal distribution. It is *relatively* easy for most cumulus parameterization to produce realistic sources of ice mass, and for most cloud parameterization to predict the subsequent decay of the ice mass. It is much more difficult for cloud parameterizations to model the evolution of the cirrus cloud system area (or more generally, the distribution of cloud optical thickness).

This Study

We are using the 2D University of Utah CRM to study the cirrus clouds that result from the life cycle of convective cloud systems. We are performing idealized 6 to 12-h CRM simulations of the life cycle of an isolated isolated cumulonimbus cloud to study the physical processes that determine the evolution of the resulting cirrus cloud system, with a focus on the processes that govern the cloud system's radiative effects.

Results

In previously reported simulations, we represented the generation of anvil clouds by adding ("injecting") cloud ice in a layer over a time period of a few hours. We found that (1) there is no spread without radiative heating, (2) mesoscale motions are required for spreading, but cloud-scale motions and/or turbulence are not, and (3) solar radiation does not reduce the spreading. The more realistic full life-cycle simulations presented here support the conclusions reached with the injected anvil simulations.

In the simulations, the spatial gradients of radiative heating at the anvil cloud edges produce a mesoscale circulation that spreads the anvil cloud outward at a signicant rate (about 1 m/s). We call this *mesoscale radiatively-induced anvil spreading* (MRAS). As the cloud spreads due to the mesoscale circulation, the radiative heating gradients also spread. The result is a positive feedback that lasts as long as there is sufficient cloud ice. As a result of the radiatively-induced anvil spreading, the simulated anvils have greater IR warming (greenhouse) effects than they would have without the radiatively-induced anvil spreading. This is due to both the greater spatial extent and the longer lifetimes of the radiatively interactive anvils.

CRM Life-cycle Simulations

The initial state for the simulations was based upon the GATE Phase-III mean sounding modified by adding the destabilizing effects of 6 h of large-scale lifting typical of a synoptic tropical disturbance. The result was a maximum cooling perturbation of 1.2 K at 635 mb, and a maximum moistening perturbation of 0.66 g/kg at 836 mb. A single convective cell was initiated by a low-level temperature perturbation.

The computational domain was 100 km x 18 km in the horizontal and vertical, respectively. The horizontal resolution was 500 m, and the vertical grid was stretched, varying from 100 m at the surface to approximately 900 m at z = 18 km. The baseline case (RAD) included interactive, ICA, cloud-scale radiative heating including solar radiation. The solar constant was 434.5 W/m^2 and the solar zenith angle was 60 deg.

The cumulonimbus cloud reaches its maximum height of 12.5 km by 3000 s. It then proceeds to detrain. At this altitude, the anvil cloud is comprised entirely of ice, and is nearly 10 km wide. Significant cloud-top radiative cooling occurs (greater than 30 K/day).

For the next 3 h, the anvil edges spread at a rate of nearly 2 m/s until the anvil is about 50 km across. This spreading is due to the combined effects of detrainment and mesoscale radiatively-induced anvil spreading (MRAS).

To isolate the effects of MRAS, we performed a simulation, called NO_RAD, that did not include radiative heating, but was otherwise identical to RAD. In NO_RAD, the anvil spreads at a lesser rate and stops spreading after only 2 h. NO_RAD spreads to about 25 km across, only half as wide as RAD.

Hovmuller plots of log10(IWP[kg/m^2]) (top panel), net IR cloud radiative forcing (CRF, W/m^2) (middle panel), and net solar CRF (W/m^2) (bottom panel).

RAD   NO_RAD   AVG_RAD

IWP

TOA IR CRF

TOA Solar CRF
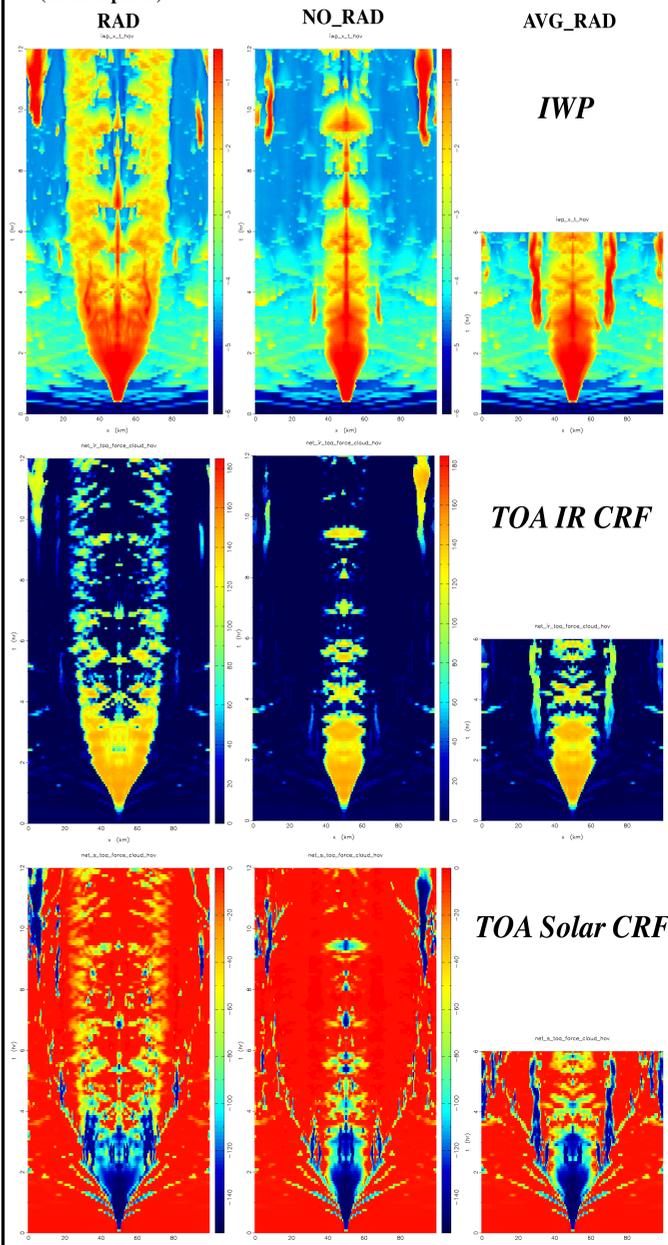
In most GCMs, clouds "feel" only the horizontally averaged radiative heating. To examine the impact of this modeling assumption, we performed a simulation, called AVG_RAD, which used this approach. In AVG_RAD, the anvil spreads like it did in NO_RAD.

However, in AVG_RAD, the pair of secondary convective cells that initiated at 3 h produce more ice than they did in either NO_RAD or RAD. Why? The destabilization due to radiative cooling is greater at the cell locations in AVG_RAD than in NO_RAD (no cooling) or in RAD (the cells lie under the anvil cirrus, which reduce the radiative cooling).

Time series for RAD (k28, red) and NO_RAD (k29, blue).

Precip Rate

IWP

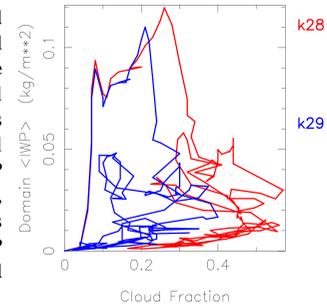### Cloud Amount

TOA IR_up

TOA Solar_up
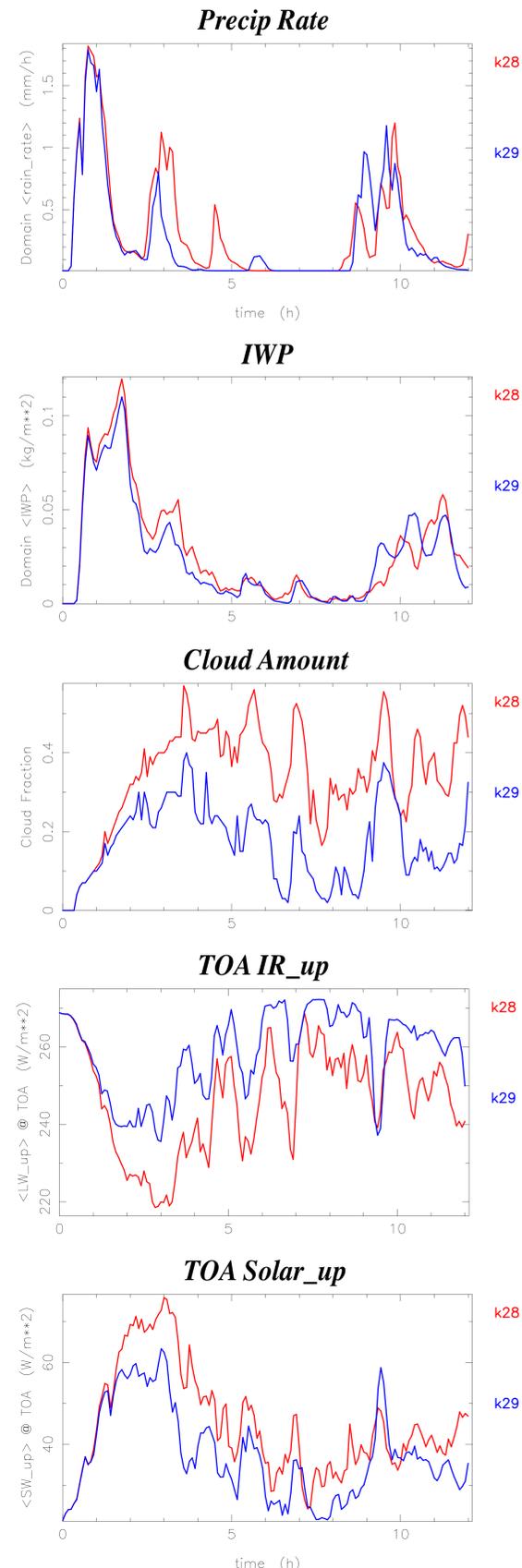
## Cloud fraction and IWP: Implications for Cloud Parameterization

The time series plots in the column to the left, as well as the trajectory and scatter plots below, clearly demonstrate that similar average IWP values can be associated with very different cloud amounts and radiative effects.

These results have important implications for cloud parameterization. To get the radiative effects of convectively generated cirrus clouds correct requires prediction of the cloud-scale distribution of IWP, which in turn requires that the cloud-scale processes that produce radiatively-induced anvil spreading be represented, which is difficult unless they are resolved, as in CRMs.

The trajectories of IWP and cloud amount (CA) for RAD (k28, red) and NO_RAD (k29, blue) are shown in the plot to the right. As the convective cell develops, the IWP (small ice) increases while CA remains small. As the anvil develops and spreads, both CA and IWP increase. After reaching maximum CA, the IWP decays while the CA remains constant. In the last stage for RAD, IWP is small, cirrus is self-sustaining, and CA and IWP are correlated.
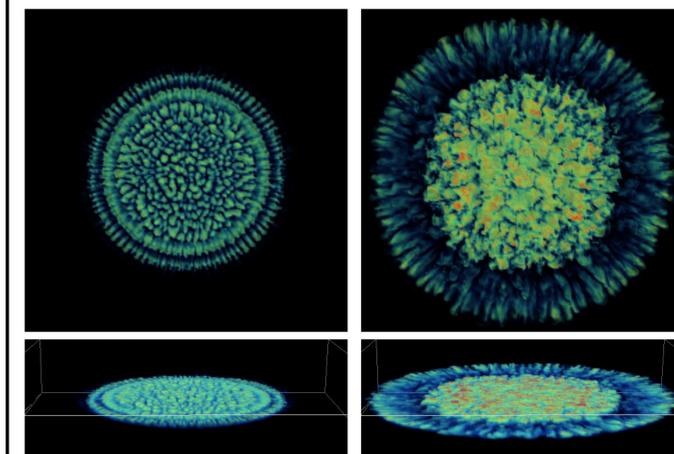

Cloud amount versus IWP for CRM (blue) and Minnis pixel-level data (red) for ARM SCM Case 3. The results are quite similar, and they demonstrate that there is not a general diagnostic relationship between cloud amount and IWP for cirrus clouds.

ARM SGP Case 3 (3-hour averages)
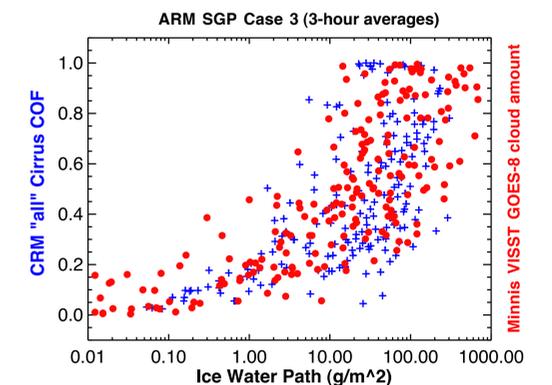
3D CRM Simulations

A small number of idealized simulations in which ice was artificially injected were run with the University of Utah 3D LES Model to determine if the spreading mechanism observed in the 2D model was simulated by a very different 3D model. The injection region was circular, rather than slab-symmetric, and the microphysical processes were simplified. Despite these differences, the resulting anvil and spread rates were similar to the 2D results. The spread rate was approximately 1.2 m/s which is nearly the same as the corresponding 2D simulations (not shown).

Volume plots of IWC for 3D LES simulation as seen from above (top), and obliquely (bottom) at 1.5 h (left), and 3 h (right).

Acknowledgments