Radiatively-Induced Anvil Spreading

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Abstract

Observations show that cirrus clouds often result from the life cycle of convective cloud systems. Figure 1 is a schematic of the life cycle of a convective system that is consistent with satellite observations of convective systems. Figure 2 shows an example of such observations. Machado and Rossow (1993), using satellite imagery, found that relatively thin high clouds constitute a large part of the area covered by such systems, especially when considering the system's entire life cycle.

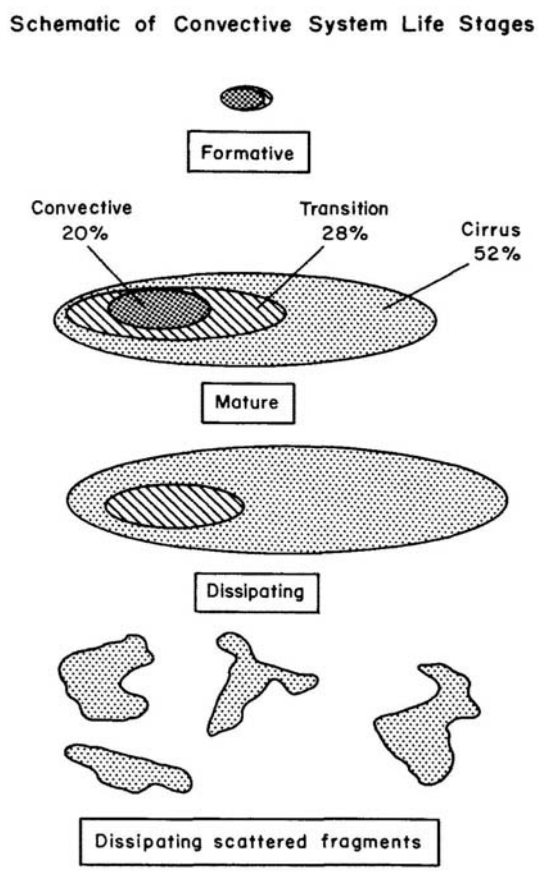

Figure 1. Schematic of the life cycle of a convective system (from Machado and Rossow [1993]).

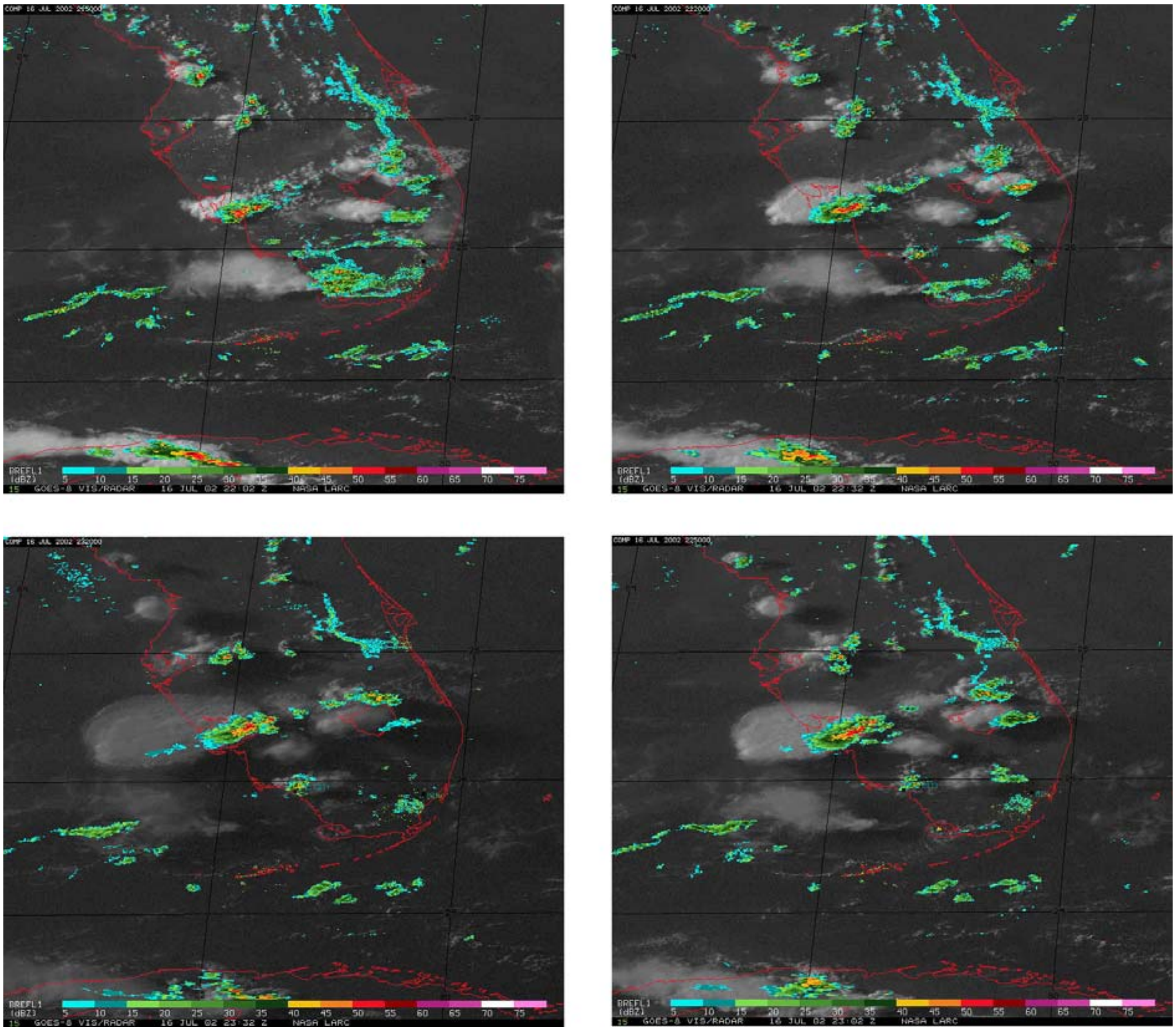

Figure 2. 1-km visible imagery with radar overlay showing anvil formation and spread on 16 July 2002 at half-hourly intervals during Cirrus Regional Study of Tropical Anvils and Cirrus Layers—Florida Area Cirrus Experiment. (http://angler.larc.nasa.gov/crystal/)

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).

In previously reported simulations (Zulauf and Krueger 2002; Krueger et al. 2004), 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 all 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 significant 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 infrared (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.

Cloud-Resolving Model Life-Cycle Simulations

We used the two-dimensional (2D) University of Utah cloud-resolving model (CRM) to study the cirrus clouds that result from the life cycle of convective cloud systems. We performed idealized 6- to 12-hour CRM simulations of the life cycle of an 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.

The initial state for the simulations was based upon the Global Atmospheric Research Program Atlantic Tropical Experiment Phase-III mean sounding modified by adding the destabilizing effects of 6 hours 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 grid size was 500 m, and the vertical grid size was stretched, varying from 100 m at the surface to approximately 900 m at z = 18 km. The baseline case (RAD) included interactive, independent column approximation, and cloud-scale radiative heating including solar radiation. The solar constant was 434.5 W/m^2 and the solar zenith angle was 60°.

The simulated cumulonimbus cloud reached its maximum height of 12.5 km by 1 hour. At this time, the anvil was nearly 10 km wide. Figure 3 (top left panel) shows that for the next 3 hours, the anvil edges spread at a rate of nearly 1 m/s until the anvil was about 50 km across. This spreading is due to the combined effects of detrainment and MRAS.

To isolate the effects of MRAS, we performed a simulation, called NO_RAD, which did not include radiative heating, but was otherwise identical to RAD. Figure 3 (top center panel) shows that in NO_RAD, the anvil spread at a lesser rate, stopped spreading after only 2 hours, and spread to about 25 km across, only half as wide as in RAD.

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. Figure 3 (top right panel) shows that in AVG_RAD, the anvil spread only slightly more than it did in NO_RAD.

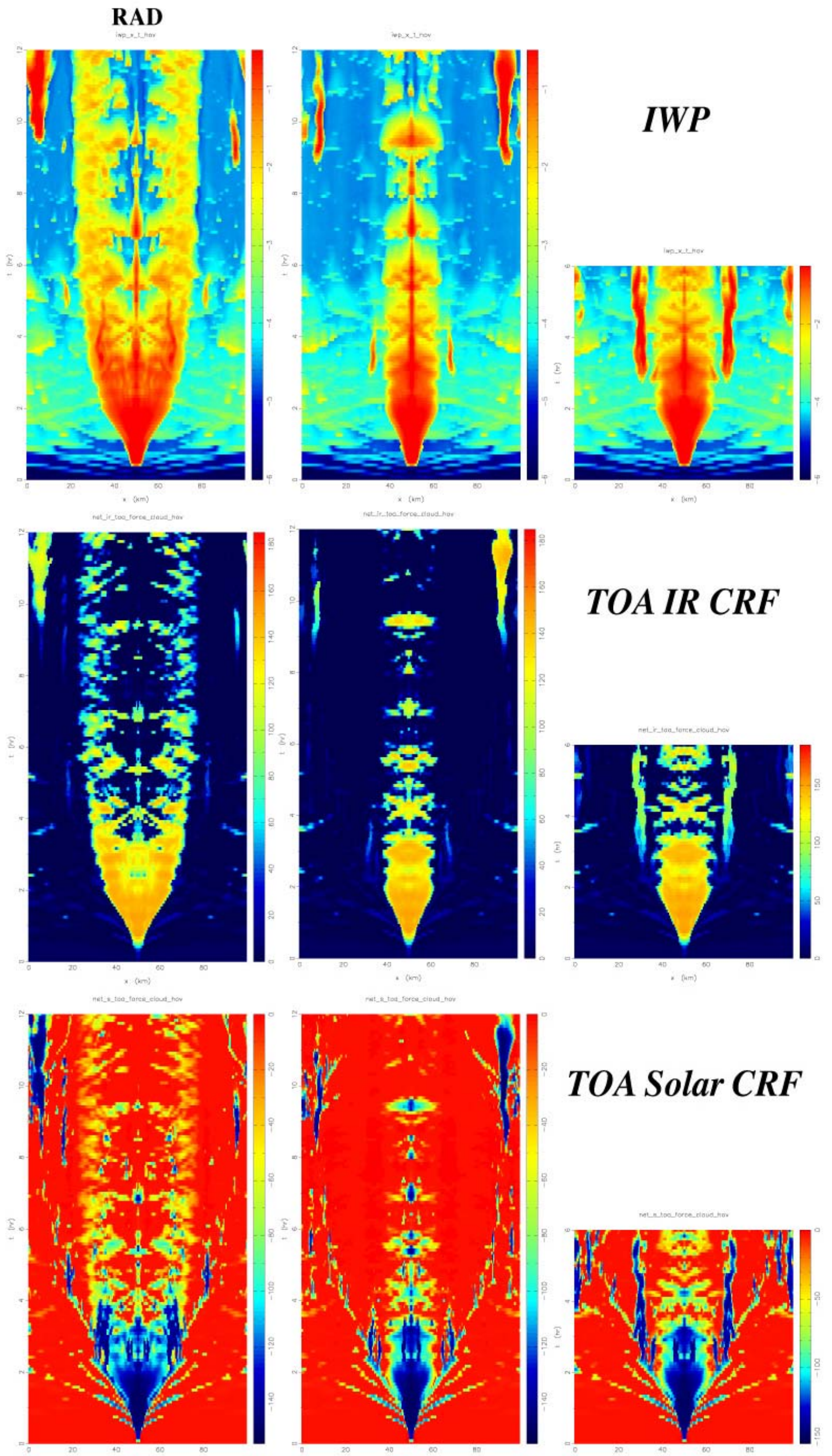

Figure 3. Hovmuller plots of log10 (IWP[kg/m^2]) (top panel), net IR cloud radiative forcing (CRF, W/m^2) (middle panel), and net solar CRF (W/m^2) (bottom panel) for the RAD, NO_RAD, and AVG_RAD CRM simulations of the life cycle of a cumulonimbus cloud and associated anvil. The horizontal domain size was 100 km and the simulation duration was 12 hours, except 6 hours for AVG_RAD.

In AVG_RAD, the pair of secondary convective cells that initiated at 3 hours produced more ice than they did in either NO_RAD or RAD. Why? The destabilization due to clear-sky radiative cooling is greater at the cell locations in AVG_RAD than in NO_RAD (no radiative cooling) or in RAD (the cells lie under the anvil cirrus, which reduce the radiative cooling). Fu et al. (1995) studied such convection-radiation interactions in detail.

The middle and lower panels of Figure 3 show the top of the atmosphere (TOA) IR and solar CRF for the 3 simulations. The impact of MRAS is largest from about 2 to 4 hours, but remains significant after 4 hours.

The time series of domain-averaged precipitation rate, ice water path (IWP), and cloud amount for RAD and NO_RAD (Figure 4, top 3 panels) show that the precipitation rate and IWP are only slightly affected

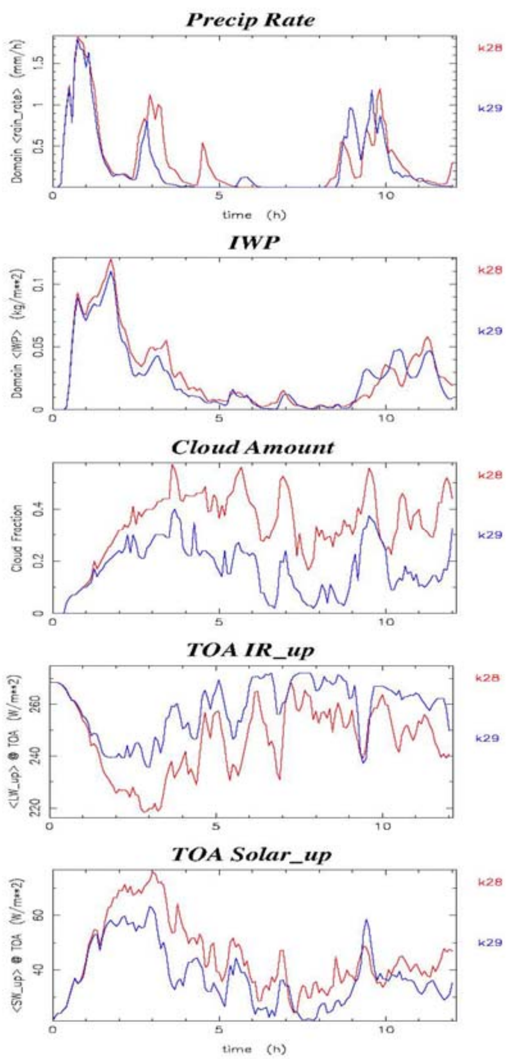

Figure 4. Time series of domain-averaged precipitation rate, IWP (ice water path), cloud amount, TOA upward IR radiative flux, and TOA upward solar radiative flux for RAD (k28, red) and NO_RAD (k29, blue).

by MRAS, in contrast to the cloud amount, which is significantly affected. These time series also show that the domain-averaged IWP and precipitation rate are strongly correlated, but that cloud amount is not well correlated with either precipitation rate or IWP.

The time series of domain-averaged TOA upward IR and solar radiative fluxes (Figure 4, bottom 2 panels) show that the large-scale radiative fluxes are significantly affected by MRAS after about 2 hours, and that the fluxes depend on both the IWP and the cloud amount.

Cloud Fraction and Ice Water Path: Implications for Cloud Parameterization

The trajectories of IWP and cloud amount (CA) for RAD and NO_RAD are shown in Figure 5. As the convective cell develops, the IWP 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 (but not for NO_RAD), IWP is small, the cirrus is self-sustaining, and CA and IWP are correlated.

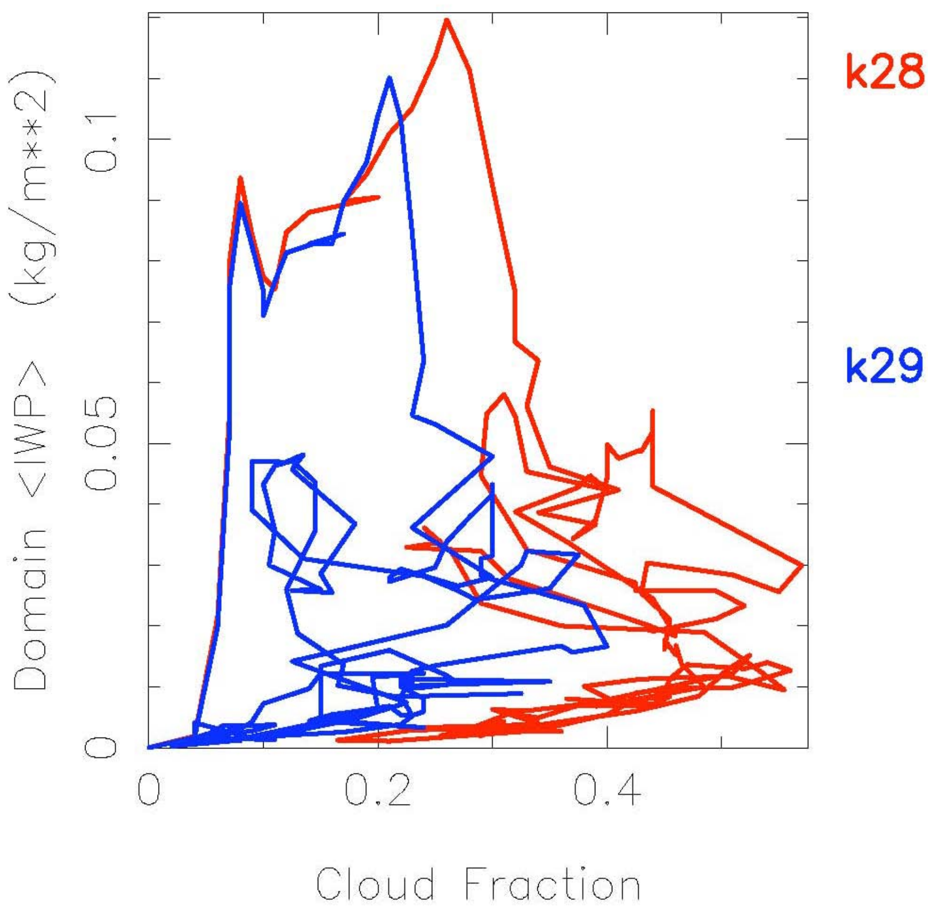

Figure 5. The trajectories of domain-averaged IWP and cloud amount for RAD (k28, red) and NO_RAD (k29, blue).

In Figure 6, large-scale cloud amount is plotted versus large-scale IWP for a CRM simulation and for the corresponding satellite retrievals. The results are quite similar. They demonstrate that there is not a general diagnostic relationship between cloud amount and IWP for cirrus clouds.

The time series plots in Figure 4, as well as the trajectory and scatter plots in Figures 5 and 6, clearly demonstrate that similar large-scale IWP values can be associated with very different cloud amounts and radiative effects. These results have important implications for cloud parameterization. To accurately determine the radiative effects of convectively generated cirrus clouds 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. This is difficult unless the anvils are resolved, as they are in CRMs.

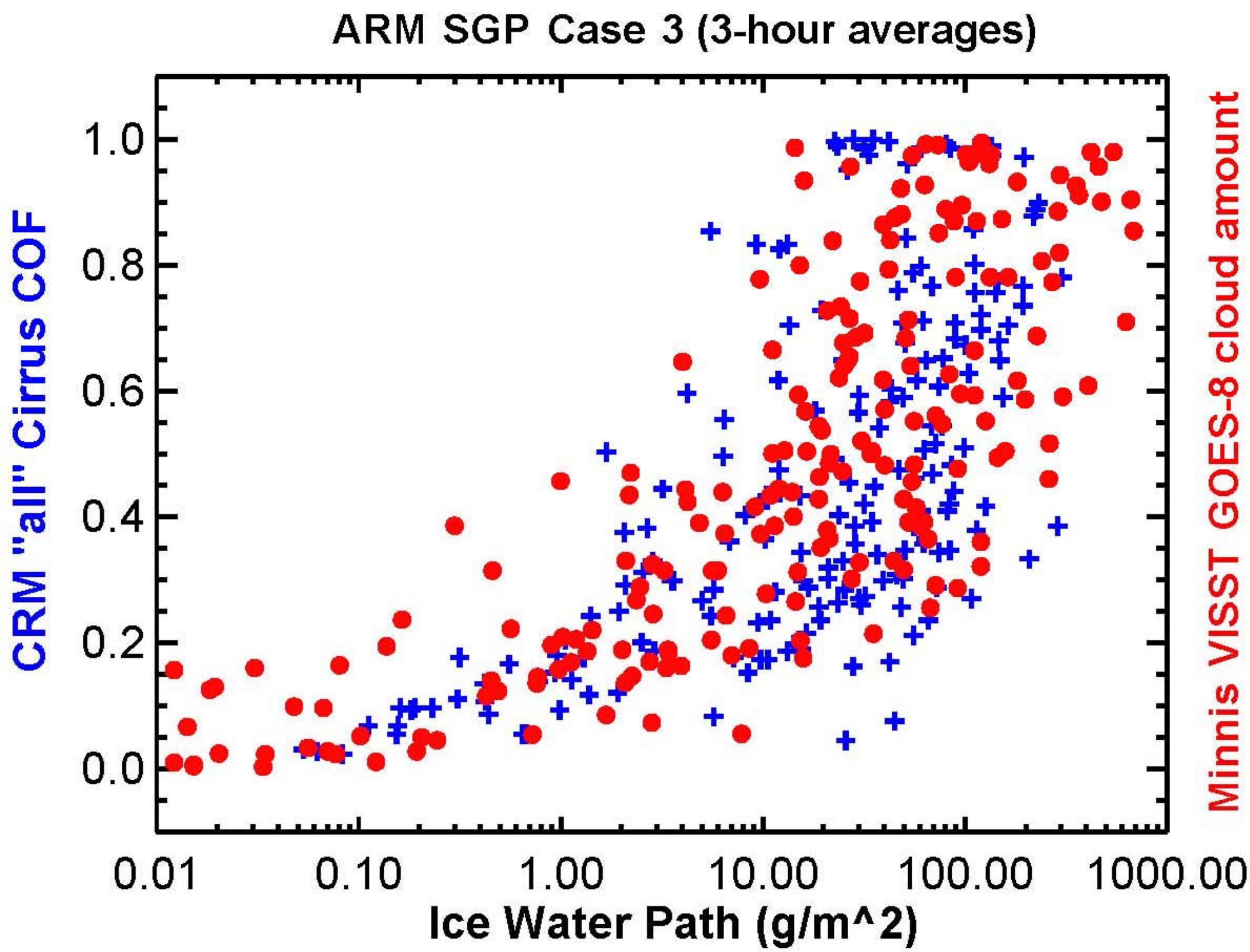

Figure 6. Large-scale cloud amount versus IWP from a CRM simulation (blue) and Minnis GOES pixel-level retrievals (red) for Summer 1997 ARM Single-Column Model Intensive Observation Period at the Southern Great Plains site.

3D Cloud-Resolving Model Simulations

A small number of idealized simulations in which small ice crystals were artificially injected were run with the University of Utah three-dimensional (3D) large-eddy simulation model to determine if the spreading mechanism observed in the 2D CRM 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).

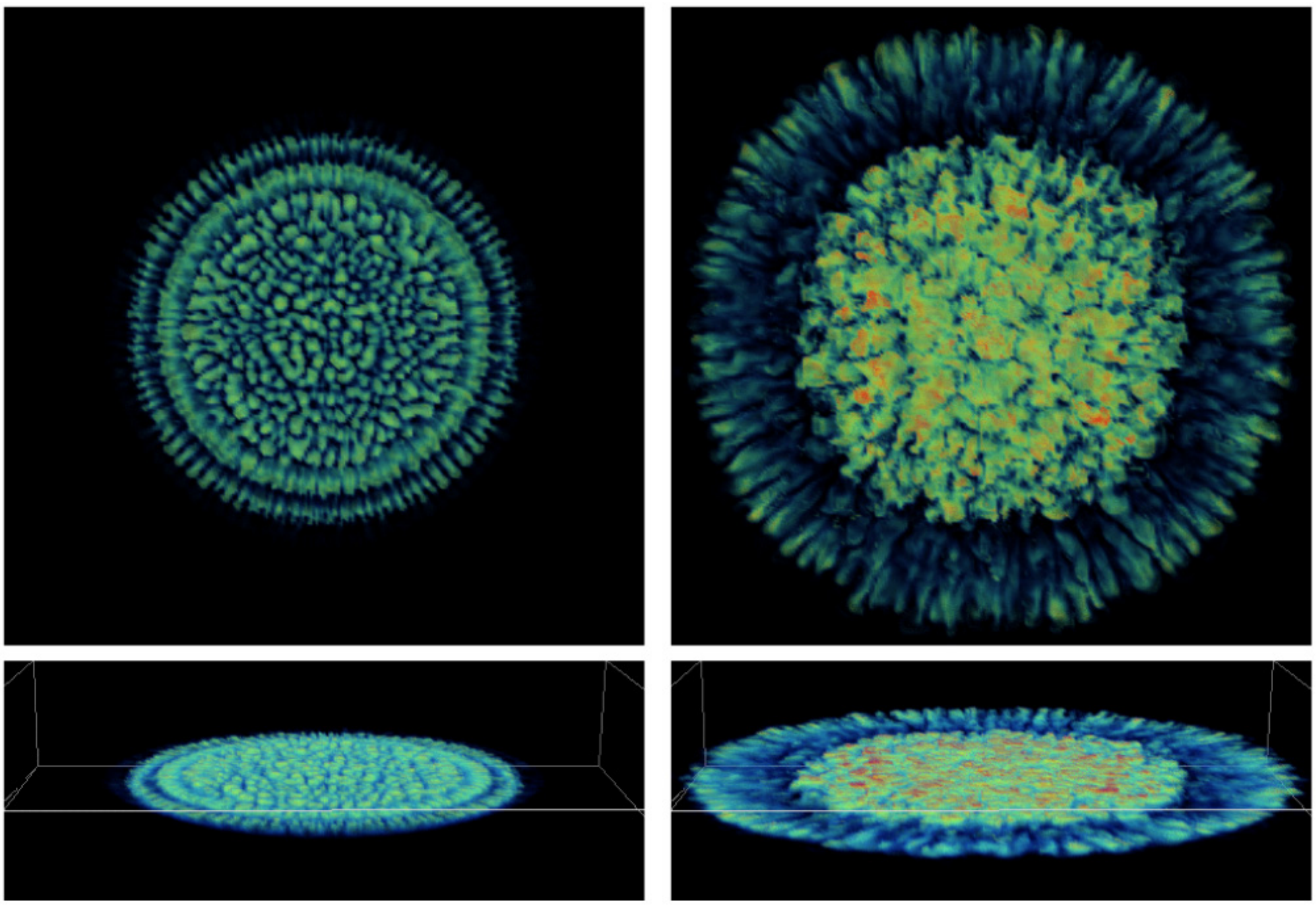

Figure 7. Volume plots of IWC for a 3D LES (large-eddy simulation) as seen from above (top), and obliquely (bottom) at 1.5 h (left), and 3 h (right).

Conclusions

There are two major conclusions from these simulations:

(1) A general diagnostic relationship between anvil cloud amount and IWP does not exist. However, there is a diagnostic relationship in the final decay stage. This suggests that a prognostic approach is generally required to determine cloud amount for convectively generated cirrus.

(2) A mesoscale circulation that spreads the anvil cloud horizontally at about 1 m/s is generated within the anvil by horizontal gradients of radiative heating at the cloud edges. 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 a sufficient cloud ice. This spreading mechanism has not been previously reported.

Contacts

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