Convective Cloud Distribution in a Cloud Resolving Model

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This is to certify that I have examined this copy of a master's thesis by

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and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
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Abstract

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The distribution of high clouds produced by a cloud resolving model is compared with satellite observations, with particular focus upon anvil cloud amount as these clouds primarily determine the net cloud radiative properties in the tropics and are important in determining the structure of heating in the atmosphere. Anvil clouds are defined as having visible optical depth between 4 and 32 and cloud top temperature less than 245 K. In three dimensional simulations using large scale forcings characteristic of particular regions in the Tropical Pacific, we determine that the model produces too few anvil clouds, although amounts of optically thick and thin high clouds compare better with observations. Top of atmosphere radiative fluxes are quite different in the simulations than observations, because of the model's inability to produce an extensive amount of anvil clouds. In an effort to improve the amount of anvil cloud produced, a suite of two dimensional runs is performed using different adjustments to the setup of the model. Changes in microphysics, resolution, and domain size do not have any significant effect on the amount of anvil clouds relative to precipitation and thick clouds. Thin and thick cloud amounts produced by the two dimensional runs do not compare as well with the observations as do those in the 3-D runs.

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DEDICATION

I dedicate this work to two people who have helped guide me since my days in Oklahoma six years ago: Daphne S. LaDue and David M. Schultz. Their encouragement and support has been essential to me throughout my career as a graduate student.

1. Introduction

In the climate system, clouds have a considerable influence on the Top-of-Atmosphere (TOA) energy budget. They affect radiative transfer in the atmosphere through their shortwave and longwave effects, the magnitude of which are determined by visible optical depth and cloud top temperature, respectively (Hartmann et al. 2001). In particular, high clouds (cloud top temperature < 245 K) are important because they are known to have large shortwave and longwave effects on the energy balance. In order to simulate TOA radiative fluxes accurately, models must produce a distribution of high clouds that agrees well with the observed distribution within the particular domain being simulated. High clouds can be partitioned into three different categories according to visible optical depth: optically thick convective cores ($\tau > 32$), medium optical depth anvil clouds ($32 \geq \tau > 4$), and optically thin cirrus ($\tau \leq 4$). In nature, anvil clouds are known to have extensive areal coverage, leading to a significant radiative impact. Therefore, it is important for models to produce realistic anvil cloud amounts and properties, in addition to realistic convective core and thin cirrus clouds.

Some ideas have been proposed about the effects of anvil clouds on the climate system and their possible role in global climate change scenarios. The Thermostat Hypothesis (Ramanathan and Collins 1991) suggests that, as SSTs exceed a critical value, anvil cloud population increases as convection becomes more intense, helping to prevent a runaway greenhouse effect through the increased reflection of solar radiation. In the Iris Hypothesis, Lindzen et al. (2001) suggest that anvil clouds have a warming effect and that their spatial coverage relative to convective cores decreases as SSTs warm, possibly helping to offset global warming. Hartmann and Larson (2002) have proposed the Fixed Anvil Temperature (FAT) Hypothesis, which states that the vertical profile of radiatively driven convergence in clear sky regions determines anvil temperature. The FAT hypothesis suggests that anvil temperature will remain constant as climate changes, allowing a simpler prediction of the radiative effect of anvil clouds. In order to better understand the role that anvil clouds play in changing climate, it is necessary to quantify the net radiative effect of anvil clouds. In a satellite based study of high clouds in the tropics, Kubar et al. (2007) define anvil clouds as having a net cooling effect through their direct radiative impacts. In this way, they define the boundary between anvil and thin clouds to be at optical depth 4. The boundary between anvil and thick clouds is taken to be 32.

Originating as outflow detraining from convective cores (i.e. cumulonimbus clouds) (Lilly 1988), anvil clouds are intimately linked to deep moist convection. Therefore, the accuracy of the simulation of anvil clouds by any model is closely related to how well it simulates convection. Cumulus convection, unfortunately, is an elusive challenge for the climate modeling community (Randall et al. 2003a). General circulation models (GCMs) are a central tool in climate research. Because cumulus convection occurs on a much smaller spatial scale than the horizontal resolution of GCMs, they rely on convective parameterization schemes. These schemes have ranged from simple convective adjustment parameterizations, early examples being Manabe and Strickler (1964) and Betts (1973), to complex mass flux schemes such as Arakawa and Schubert (1974) and Zhang and McFarlane (1995). Unfortunately, it is doubtful that convective parameterization schemes lead to accurate simulation of convective clouds.

They do not contain explicit dynamics of anvil clouds. Consequently, anvil clouds are probably not simulated very well by GCMs, although some effort has been made to improve their representation in GCMs (Gregory 1999; Ringer and Allan 2004). Thus, it is unlikely that GCMs produce a realistic distribution of high clouds with thin, anvil, and thick clouds as in the observed properties.

Cloud Resolving Models (CRMs) are designed to simulate convection explicitly. They have much finer horizontal resolution than GCMs, typically 1 to 5 km compared with only 200 to 300 km in GCMs. At such high resolution, the vertical motions of cloud-scale convective plumes are assumed to be resolved using the prognostic equations of motion, so the convective parameterization is turned off. However, cloud microphysical processes and subgrid turbulent transport must still be parameterized. Because of the high computational cost of 3-D CRM simulations, domain size is often limited to an order of a few hundred to 1000 km. An early use of a 3-D CRM in a climate study was by Tompkins and Craig (1998). CRM validation methodologies have involved comparing the results of both CRMs and Single Column Models (SCMs) to observations. Luo et al. (2005) demonstrate that the UCLA/CSU CRM produces more realistic cirrus cloud properties than the SCM version of the Global Forecast System Model. Using a variety of both CRMs and SCMs to simulate ARM observations, Randall et al. (2003b) demonstrate that CRMs produce smaller biases in vertical profiles of water vapor, temperature, and cloud occurrence than SCMs. These studies imply that the resolved convective processes in CRMs are indeed superior to the parameterized processes in GCMs, because SCMs are essentially tests of GCM convective parameterizations (Betts and Miller 1986; Randall et al. 1996). Because CRMs perform better than SCMs in radiative convective equilibrium simulations, it has been proposed that GCM simulations may improve if their convective parameterization schemes are replaced with a CRM embedded in each grid cell, a process referred to as "super parameterization" (Grabowski 2001; Randall et al. 2003a). These schemes have shown promise in helping models produce realistic Madden-Julian Oscillations (Grabowski 2003b; Randall et al. 2003b). However, Ovtchinnikov et al. (2006) show that a GCM using the super parameterization convective scheme produces too little cloud compared to observations, including too little high cloud. Wyant et al. (2006) compare clouds produced by a GCM using super parameterization to ISCCP data, showing that, in different dynamical regimes, the model tends to either over-predict or under-predict cloud fraction.

Continued analysis of CRMs is necessary to validate their accuracy in climate simulations and to determine how successful they might be if employed as "super parameterizations." Therefore, more effort should be devoted to methodologies that compare CRMs with observational data, particularly to studies that assess the TOA energy budget in the tropics. Comparing the Advanced Regional Prediction System/Langley Research Center (ARPS/LaRC) CRM to satellite observations, Eitzen and Xu (2005) showed differences in probability density functions (PDFs) of albedo and outgoing longwave radiation (OLR) between the model and observations. Luo et al. (2007) found that a CRM intended for use as part of a super parameterization tended to underestimate higher albedos. In another CRM verification study, Blossey et al. (2007) compared the System for Atmospheric Modeling (SAM) to KWAJEX observations, showing persistent biases in albedo and OLR due to an insufficient amount of high clouds during periods of low to moderate precipitation. Such biases suggest the possibility of a lack of anvil clouds in the SAM simulations. Further studies that assess the distribution of high clouds produced by CRMs in tropical simulations are needed because of the aforementioned relationship between high clouds and TOA radiative budgets.

This thesis analyzes the distribution of high clouds produced by the SAM model run in a tropical domain and compares them to distributions observed from space by the MODIS instrument, with particular interest in anvil clouds. PDFs and domain averages of albedo and OLR are also examined to help quantify the relationship between clouds and the TOA energy budget in the model. Chapter 2 provides some background information related to anvil clouds. Chapters 3 and 4 present three dimensional simulations. Chapter 5 introduces two-dimensional methodology that is used to test how changes to the model may affect anvil cloud amount, and chapter 6 details these 2-D experiments. Finally, chapters 7 and 8 offer discussion and conclusions.

2. Background

In our schematic of convective systems, anvil clouds are formed by material detraining from convective cores (figure 2-1). The anvil cloud thins as it spreads away from the core, eventually becoming optically thin enough to be classified as high thin cirrus cloud. The detrainment level, where anvil clouds form, can be located at the tropopause in strong midlatitude thunderstorms with overshooting tops (Adler and Mack 1986). However, in the tropics, detrainment occurs well below the tropopause (Hartmann and Larson 2002). Kubar et al. (2007) demonstrate that detrainment in tropical convective systems is consistent with a circulation in which clear sky convergence caused by radiative cooling determines the level of detrainment.

Immediately after detraining from the convective core, the air in anvil clouds is expected to have properties similar to the air inside the core. Indeed, the air in newly formed anvil clouds is ice laden and turbulent, after which radiative heating continues to produce turbulence which helps to sustain the existence of the anvil cloud (Lilly 1988). Garrett et al. (2005) suggest that radiative heating primarily causes the anvil cloud to spread horizontally through density currents, because heating is confined near the cloud top and base due to the cloud being comprised of many small ice particles. In any case, the physical mechanisms sustaining anvil clouds help to create impressively large cloud structures. Anvil clouds associated with intense tropical convective systems are known to have long lifetimes and to spread vast distances from the convective core, accounting for a large percentage of the precipitation produced by such systems (Leary and Houze 1980). Large mesoscale convective systems (MCSs) over the Western Pacific Warm Pool can form long lived structures called “super clusters” which can extend for thousands of kilometers and last as long as 2 days (Mapes and Houze 1993; Chen et al. 1996), implying that the anvil clouds associated with such systems have a large effect on tropical climate.

It is useful to partition high clouds into categories based on visible optical depth in climate studies, because it provides a way of concisely distinguishing between clouds with presumably different shortwave radiative effects. Indeed, the International Satellite Cloud Climatology Project (ISCCP) D-series dataset partitions high clouds in such a manner (Rossow and Schiffer 1999). Kubar et al. (2007) also partitioned high clouds into three categories based on visible optical depth, defining anvil clouds as high clouds of medium optical depth. High thin clouds have a net warming effect in this partitioning system, while anvil clouds and high thick clouds have a net cooling effect. Determining the amount of each category as a function of rain rate, they noted larger abundance of both optically thin high cloud and anvil cloud in a region over the Western Pacific Warm Pool, compared to a convective region over relatively cooler sea surface temperature in the Eastern Pacific (figure 2-2). However, they found nearly the same amount of optically thick high cloud in both regions in relation to precipitation rate.

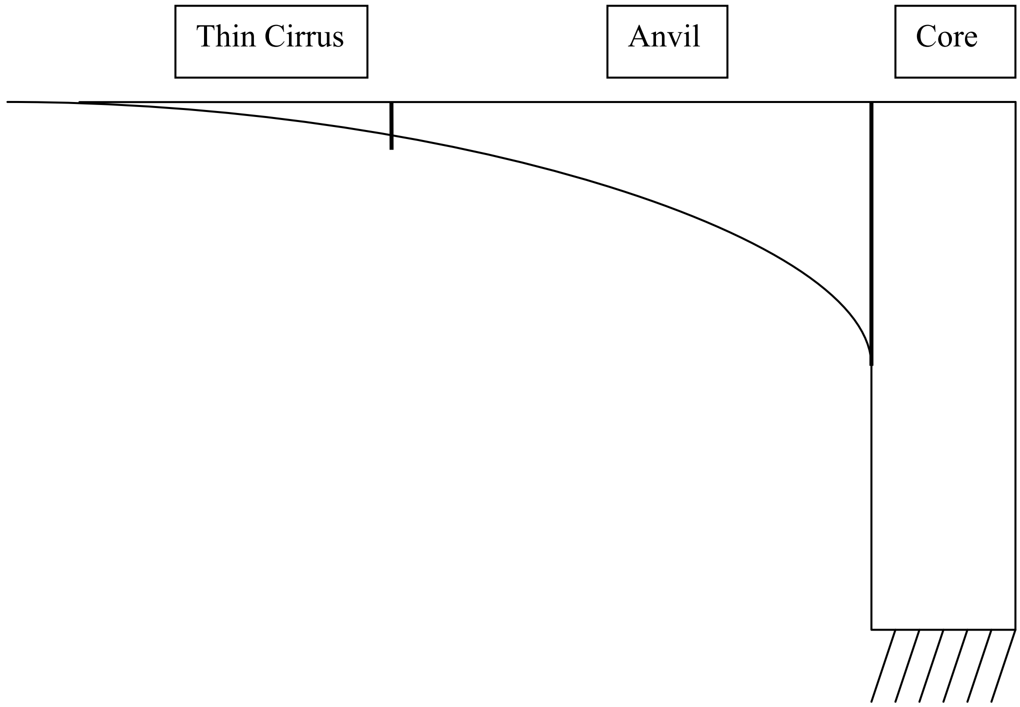

Figure 2-1. Schematic of a convective cloud system showing convective core with attached anvil and thin cirrus.

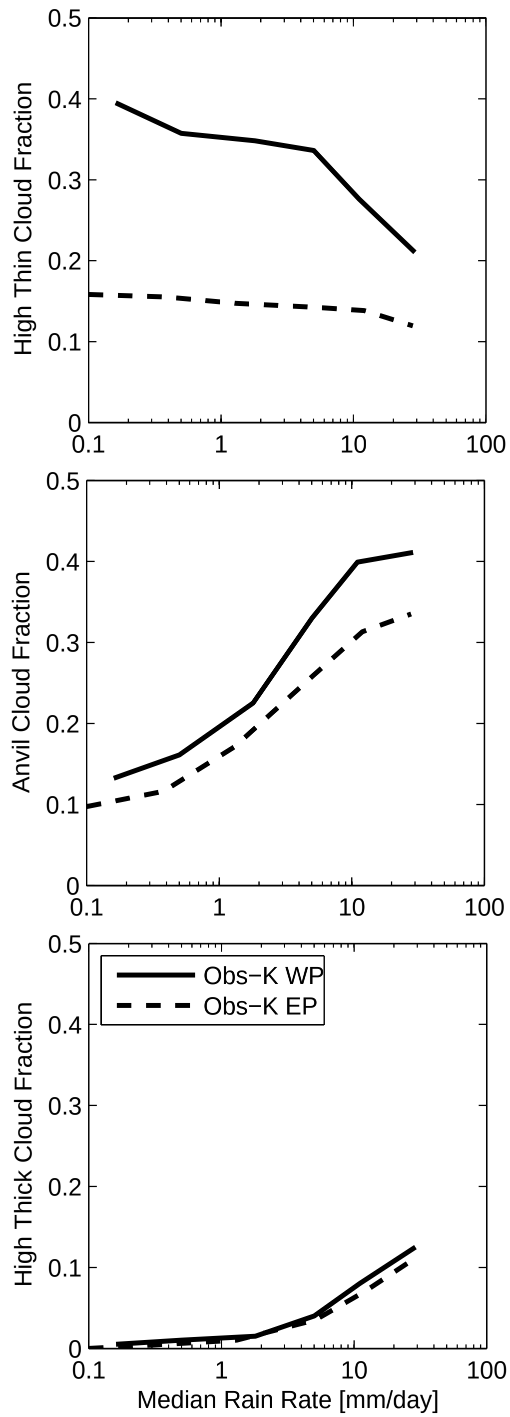

Figure 2-2: Cloud fraction composites with rain rate from Kubar et al. (2007).

3. Three-Dimensional Methodology

We employ the System for Atmospheric Modeling (SAM) version 6.3, a three dimensional CRM developed at Colorado State University (Khairoutdinov and Randall 2003), using the output of simulations carried out by Peter Blossey and originally designed by Chris Bretherton. Convectively active regions of the Tropical East and West Pacific are simulated and compared to satellite data. In each of these two regions, a unique profile of vertical motion has been documented (Back and Bretherton 2006). We designate three categories of high cloud (cloud top temperature < 245 K) according to visible optical depth, in which anvil clouds are those high clouds of medium optical depth here defined as greater than 4 and less than or equal to 32. High thin clouds have optical depth less than or equal to 4, and high thick clouds (i.e. convective cores) have optical depth greater than 32. This system for partitioning high clouds is identical to that used by Kubar et al. (2007), where anvil clouds generally have a net cooling effect (figure 3-1). The method used to calculate optical depth in the model is discussed later in this chapter.

The SAM simulations are compared to satellite based observations from the two regions being simulated: the East Pacific (7-9N, 140-120W) and the West Pacific (5-7N, 140-160E). The satellite data comes from the Aqua MODIS Joint Level-2 Dataset, containing information about cloud fraction, optical depth, and cloud top temperature. These fields are used to determine fractions of each cloud category in 1 degree by 1 degree chunks, averaged over a 3 day time scale. In each chunk, a corresponding rain rate is obtained from the Advanced Microwave Scanning Radiometer collocated on the Aqua Satellite. All observations are made at 1:30 p.m. local time. The interested reader is referred to Kubar et al. (2007) for more detailed discussion of the satellite methodology.

In the 3-D SAM simulations, we use a horizontal domain of 256 by 256 km with 1 km resolution. The model has 64 levels in the vertical. Spacing between levels varies from 75 m at the surface to 400 m through most of the troposphere and finally 1 km in the "sponge region" (top 30% of domain). The purpose of the sponge region is to prevent upward propagating gravity waves from bouncing off the rigid lid at the top of the model and traveling downward. To represent near equatorial conditions, the Coriolis parameter is set to zero. The model does not use a planetary boundary layer scheme apart from enhanced vertical resolution near the surface and skin friction. Also, it does not include an ocean mixed layer. The model utilizes a Smagorinsky scheme for subgrid scale turbulent transport and the radiation scheme from CAM 3.0. No diurnal cycle of insolation is used. A nominal 6 second time step is used, which can be decreased in situations where the CFL limit might be violated. Radiation is computed every 6 minutes.

The prognostic thermodynamic variables in SAM are non-precipitating water, precipitating water, and liquid/ice moist static energy. Non-precipitating water includes water vapor, cloud liquid, and cloud ice, while precipitating water includes rain, snow, and graupel. Partitioning between hydrometeor species is based on temperature. Supersaturation of water vapor is not allowed. In the CAM 3.0 radiation scheme, water vapor, cloud liquid, and cloud ice are all radiatively active, but precipitating hydrometeors are not. The default one-moment bulk microphysical parameterization of SAM is used. Although cloud ice is considered to be non-precipitating, it is allowed to have a nonzero terminal velocity. The interested reader is referred to Appendix D of

Khairoutdinov and Randall (2003) for a detailed description of the default SAM microphysics. We make one noteworthy change by introducing a relationship whereby cloud ice fall speed is calculated as a function of ice water content following Heymsfield (2003), replacing the default parameterization in which cloud ice fall speed is fixed at a constant value of 0.4 m/s. The Heymsfield (2003) relation will be discussed further in Chapter 6.

In the simulations, large scale winds and SST are specified. An idealized profile of zonal wind is specified, decreasing linearly from 5 m/s at the surface to zero at the tropopause in both runs, and zonal winds are nudged to these prescribed values on a 2 hour time scale. This shear profile was chosen to be weak yet inhibit domain-scale self-aggregation of convection (Bretherton et al. 2005). Different profiles of large scale vertical velocity are imposed in the East and West Pacific simulations, which are equivalent to the climatological mean profiles obtained by Back and Bretherton (2006) using reanalysis data (figure 3-2). Each profile has been normalized in amplitude to produce a domain-mean rainfall rate of approximately 15 mm/day. Thus differences between the clouds in the simulations are due to the profile shape, not the overall domain-mean intensity of convection. Qualitatively, these profiles are described as "bottom heavy" in the East Pacific and "top heavy" in the West Pacific. SST is fixed at 302.49 K in both simulations to further assure that differences between the two simulations are a result of the imposed vertical motion profiles, rather than differences in SST.

The simulations are run for a total of 10 days, after having been run on a smaller 64 by 64 km domain for 50 days to a state of radiative convective equilibrium (RCE). Instantaneous fields are output every hour. The first day is a spinup period for convective circulations. Using the last 9 days of model output, which describe the RCE state, we determine the abundance of high thin, anvil, and high thick clouds. The amount of each category of cloud and its amount relative to the other two categories are both important in determining whether SAM produces a realistic convective cloud distribution. Because cloud category and cloud fraction are not model output variables, they are calculated by a post processing script, using a column-by-column algorithm. Cloud top temperature and total column visible optical depth are used in the determination of cloud category in each column, to facilitate comparison with satellite observations. In each layer of the column, visible optical depth is calculated using liquid/ice water path and effective radius:

$$\tau_{layer} = \frac{3}{2}\frac{LWP}{r_{el}} + \frac{3}{2}\frac{IWP}{r_{ei}},$$

where LWP and IWP are in g m^{-2}, and r_{el} and r_{ei} are in microns. Total column visible optical depth is then calculated as the cumulative sum of the optical depth in every layer of the column. Because we desire to determine cloud top temperature using a technique similar to that of the satellite observations with which we will compare the model, a TOA downward approach is used, similar to methodology employed by Klein and Jakob (1999) to compare clouds in the ECMWF model to ISCCP satellite data. Cloud top temperature in the column is determined as the temperature at the top of the layer where cumulative optical depth from TOA exceeds 0.1, which is the minimal optical depth requirement that we impose for the column to contain a cloud. Klein and Jakob (1999) also used 0.1 as the minimum optical depth of a cloud, and experimentation with smaller minimal depth thresholds had negligible effects on our results. If the 0.1 optical depth threshold is never reached within a column, then that column is designated as clear sky.

Otherwise, the high cloud category is determined by the optical depth of the column, provided that cloud top temperature is less than 245 K. To determine cloud fraction, the domain is divided into blocks of 64 by 64 km, and cloud fractions in each block are calculated by dividing the number of columns containing each cloud category by the total number of columns in the block. The block size of 64 by 64 km is chosen to best represent an area of about 100x100 km, which is the size of the 1 by 1 degree regions used to determine cloud cover statistics in the satellite data with which we will compare our results.

We examine cloud fraction as a function of rain rate. Rain rate is directly related to the latent heating term that drives the tropical circulation, so the relationship between rain rate and cloud amount is a fundamental quantity of importance in climate research. Thus, our strategy is to composite cloud fraction with rain rate. For each block, mean rain rate is obtained by averaging the surface rain rate of all the columns within the block. Using hourly output fields from the entire RCE state, an aggregate of cloud fractions and mean rain rates is formed. Percentiles of rain rate are calculated from the mean rain rates, ignoring mean rain rates less than 0.1 mm/day so that the percentiles will reflect a larger range of rain rates. We next bin cloud fraction by percentile of rain rate. Ultimately, we obtain a relationship between average cloud fraction in each bin and that bin's median rain rate. This relationship was also investigated in the methodology of Kubar et al. (2007) and is used here to compare the results of the model to the satellite data.

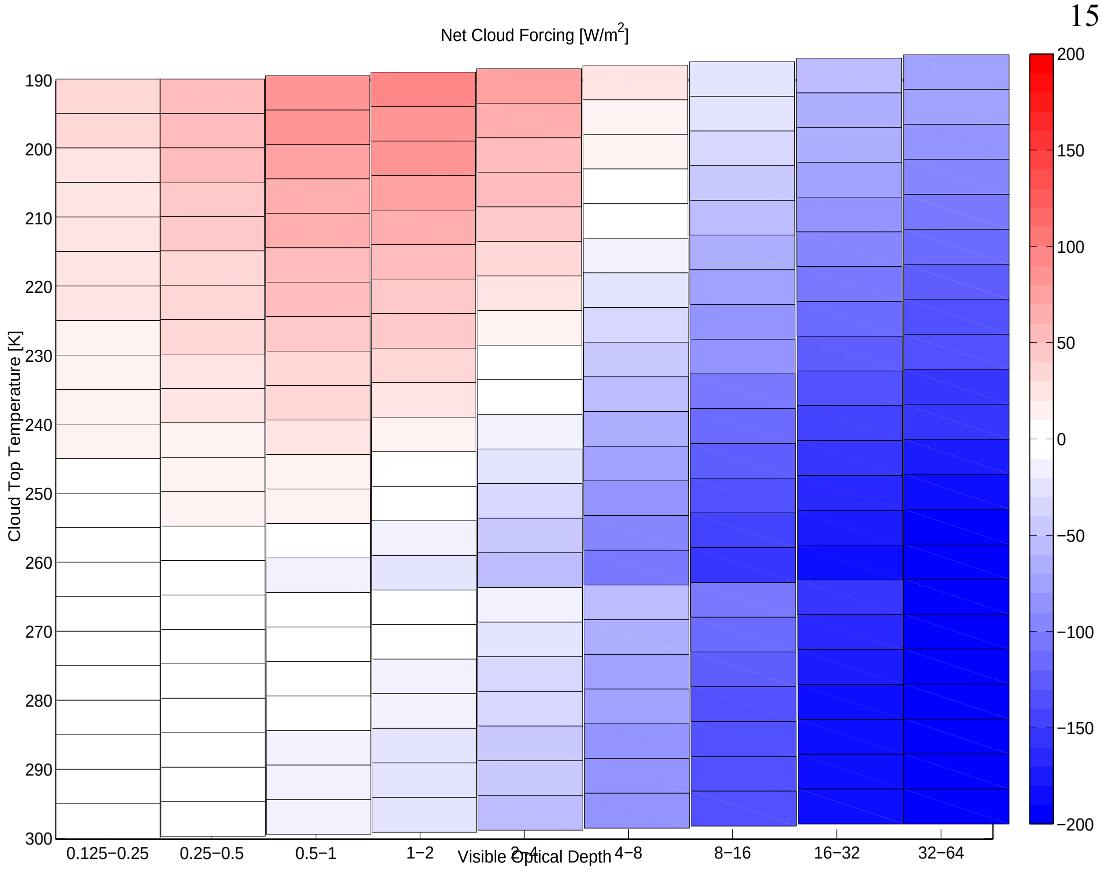

Figure 3-1: Histogram of net cloud radiative forcing binned by cloud top temperature and visible optical depth.

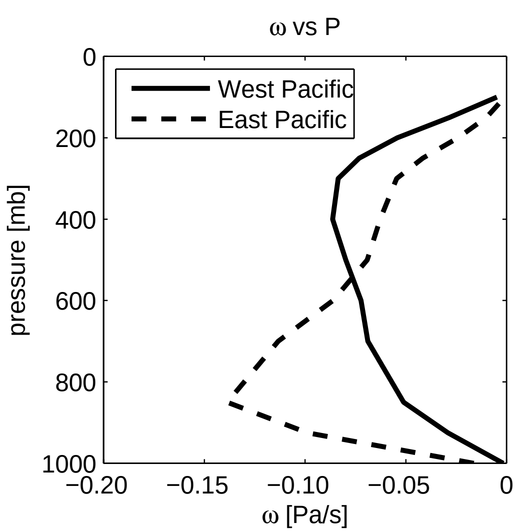

Figure 3-2: Vertical motion profiles in West and East Pacific obtained from reanalysis data by Back and Bretherton (2006).

4. Three-Dimensional Results

Although observations show a clear relationship between anvil clouds and rain rate, anvil cloud fraction varies little with rain rate in the simulations (figure 4-1). Furthermore, anvil cloud fraction in the simulations is strikingly small compared with observations. Anvil cloud fraction in both simulations never exceeds about 10% for any particular rain rate. For the lowest rain rates, anvil cloud fraction is only about half as high as observed. The observations show anvil cloud fractions as high as 40% and 45% at high rain rates in the East and West Pacific, respectively. Blossey et al. (2007) also show that SAM tends to under-produce high clouds of medium optical depth (i.e. anvil clouds). Another important finding of the observations is that, for a given rain rate, there are more anvil clouds in the West Pacific than the East Pacific. In the simulations, the ratio of West to East anvil cloud amount is about the same as in observations. However, it is disappointing that the mean anvil cloud amounts in the model are only 1/4 to 1/2 of that in the observations.

Thin cloud fraction is somewhat independent of rain rate in both the East and West Pacific simulations. However, a decrease in thin cloud fraction occurs at the highest rain rates, which is probably due to convective cores being the dominant cloud species in places where precipitation is most intense thus decreasing the probability of finding thin clouds in those locations. In the observations, thin cloud fraction decreases even more noticeably with increasing rain rate than in the model. Average thin cloud fractions in the simulations are around 17% and 30% in the East and West Pacific, respectively. These thin cloud fractions are systematically larger than observations. In comparison, Blossey et al. (2007) find that SAM only slightly over-predicts high thin cloud fraction.

The simulations show a clear relationship between thick cloud fraction and rain rate. Observations also show a strong dependence of thick cloud fraction upon rain rate. Additionally, the observations indicate that thick cloud fraction is nearly identical in both the East and West Pacific. The simulations do well, producing a relationship between rain rate and thick cloud fraction that agrees excellently with observations. By contrast, Blossey et al. (2007) show that SAM under-predicts high thick cloud fraction.

The 3-D model simulations appear to produce the observed relationship between high thick cloud fraction and precipitation rate. High thin cloud fractions are slightly larger than observations, and the amount of anvil cloud is greatly under-predicted. Because the cloud fraction-rain rate composites only convey information about cloud amount in places where precipitation is occurring, there is a possibility that our methodology fails to detect some anvil clouds, if they spread vast distances from the convective core and populate blocks where precipitation is either extremely light (less that 0.10 mm/day) or zero. The model might produce a realistic amount of anvil clouds in this scenario, but the cloud fraction-rain rate composite methodology would fail to detect them, biasing our results toward a low number of anvil clouds. To eliminate this as a possibility, we examine domain average cloud fraction. If the model is indeed under-producing anvil clouds, then domain averages will clearly show this. Domain average anvil cloud fraction is indeed smaller than observations (figure 4-2), confirming that the 3-D simulations do not produce enough anvil cloud. Also, domain average high thick cloud fraction agrees well with observations, as suggested by the composites with rain rate. Domain average high thin cloud fraction is slightly higher than observations in the East Pacific and nearly agrees with observations in the West Pacific. Although the rain rate composites suggest that the model over-produces high thin cloud in the West Pacific, the unexpected agreement with observations may indicate that high thin clouds in the West Pacific are most numerous in low rain rate blocks far from convective activity, perhaps sustained by gravity waves or the mean rising motion in the upper troposphere in the West Pacific. Domain average rain rate in the simulations is significantly larger than observations, which is probably a result of the specified vertical motion constantly initiating convection. This debunks any speculation that the model might not be producing enough anvil cloud because it is not producing enough rain, because the model is instead producing too much rain. To concisely state the low amount of anvil cloud in the 3-D SAM simulations, the ratio of anvil cloud to high thick cloud is compared with observations (figure 4-3), indicating that the ratio is much smaller in the model. The lack of anvil clouds in the model suggests that TOA radiative fluxes might be simulated incorrectly.

To investigate whether the lack of anvil clouds significantly affects the TOA energy budget, we examine PDFs of albedo and OLR. The PDFs are constructed from values of albedo and OLR at every point in the domain of the model as well as in the corresponding observational domain. To construct PDFs from the observations, the radiative transfer model of Fu and Liou (1993) is used to calculate albedo and OLR in the domain of the observations, based upon the MODIS observed cloud properties. The cloud properties used in the radiative transfer calculations are based upon pixel level

MODIS data, so that they can be directly comparable to the grid point level PDFs obtained from the model.

In the observations, the PDF of albedo has two modes (Figure 4-4). The first mode, centered at 0.15, corresponds to clear sky albedo. The second mode is a broad peak at higher albedo. In the simulations, the higher albedo mode is absent. Similar behavior is evident in the PDF of OLR (Figure 4-5). Observations show one mode at high OLR and another mode at low OLR, with the low OLR mode being absent in the simulations. Thus, it seems that the lack of anvil clouds in the simulations is creating biases in albedo and OLR. The domain average albedo is in fact significantly smaller in the simulations than observations (figure 4-6), although domain average OLR agrees somewhat better probably because it depends much more on cloud top temperature than optical depth. It is necessary for the model to produce more extensive anvil cloud coverage in order to improve the simulation of the TOA energy budget. In the next chapter, we will apply a two-dimensional version of SAM to investigate the sensitivity of the anvil cloud fraction to model parameters.

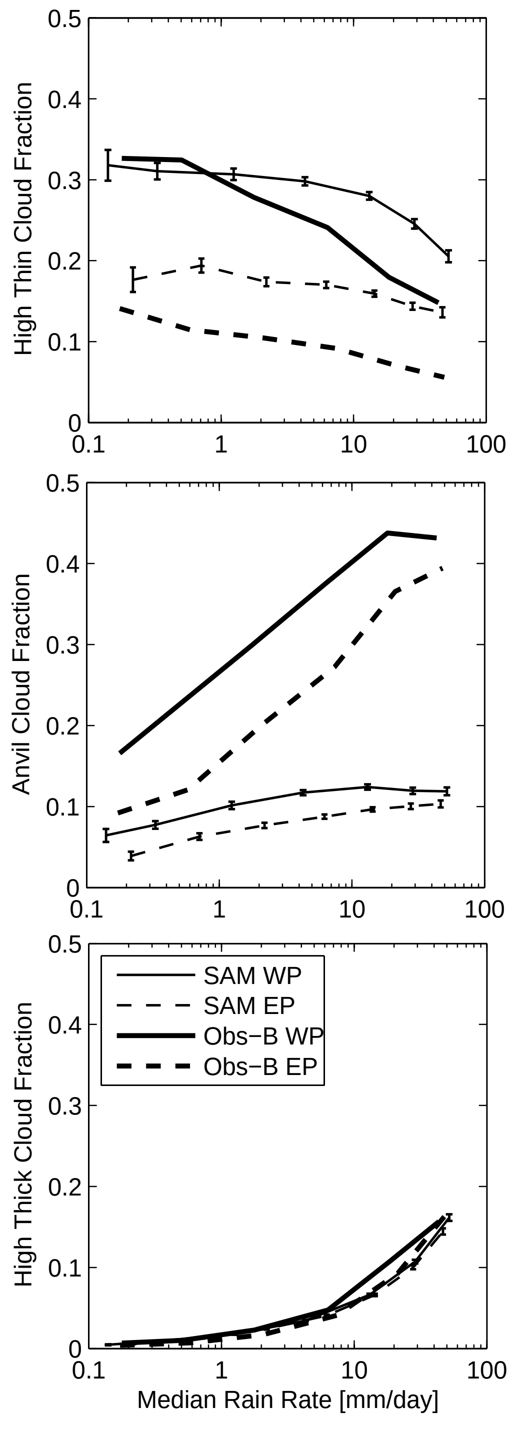

Figure 4-1: Comparison of 3-D SAM simulations in West and East Pacific domains to satellite observations.

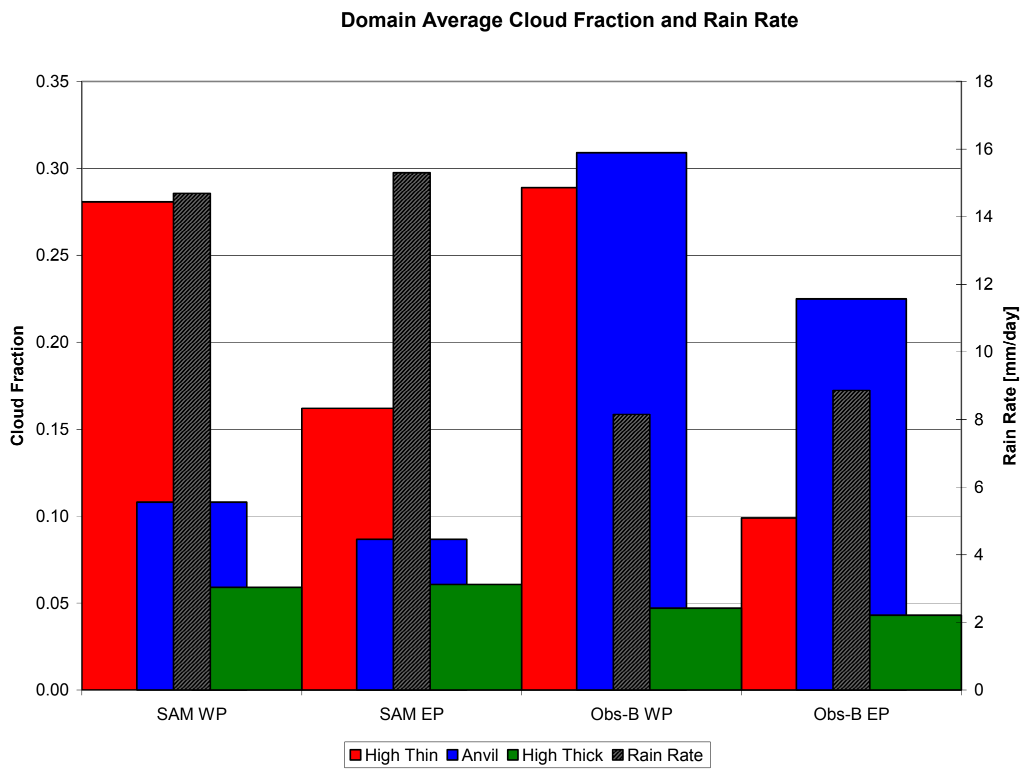

Figure 4-2: Domain average ratio of high thin, anvil, and thick cloud fraction with domain average rain rate.

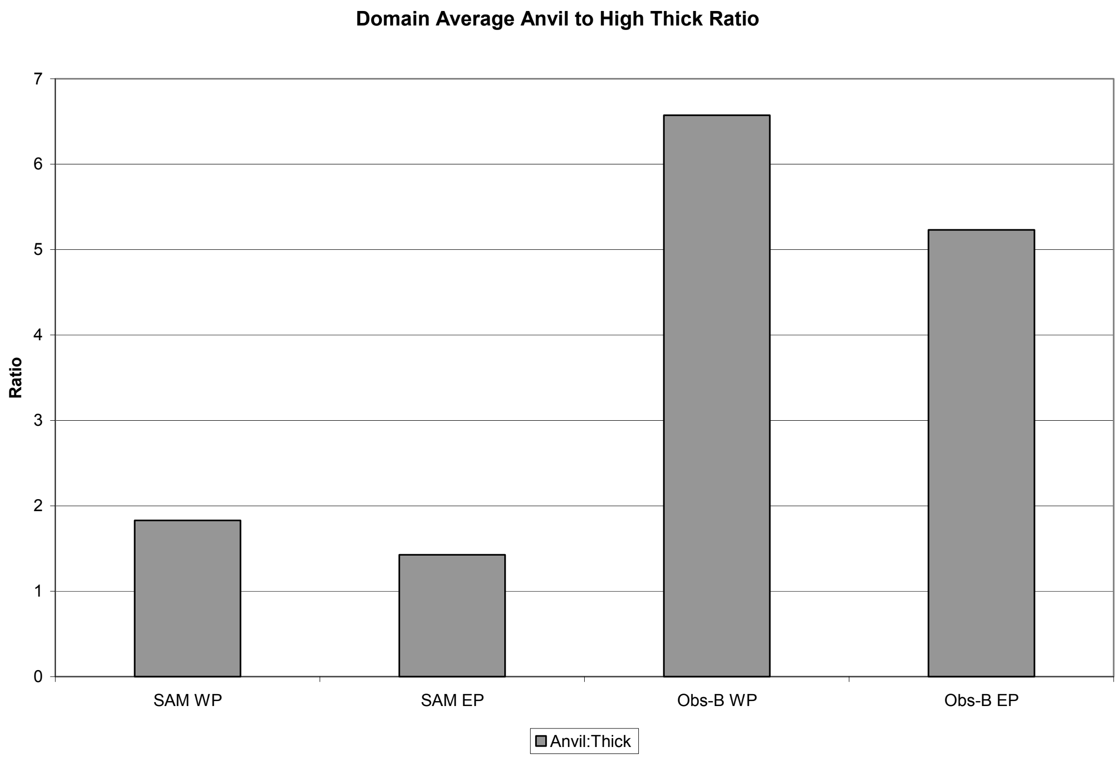

Figure 4-3: Domain average ratio of anvil cloud fraction to high thick cloud fraction.

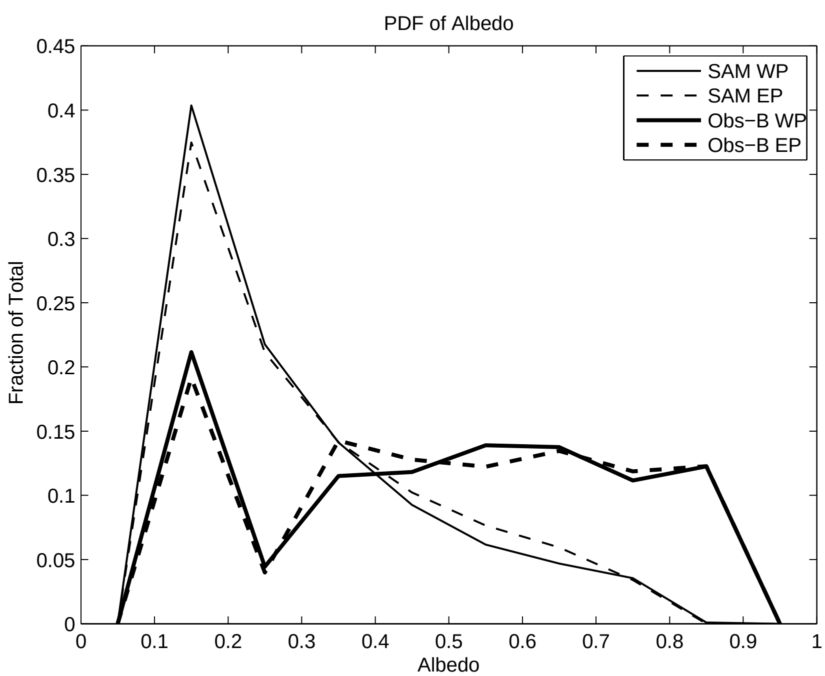

Figure 4-4: Probability density functions of albedo in the 3-D simulations and observations.

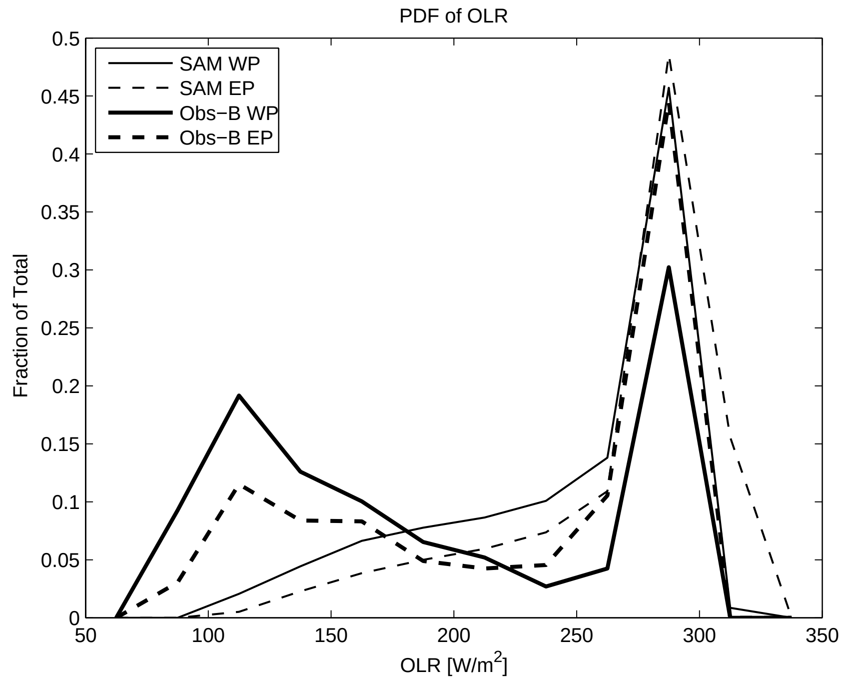

Figure 4-5: Probability density functions of OLR in the 3-D simulations and observations.

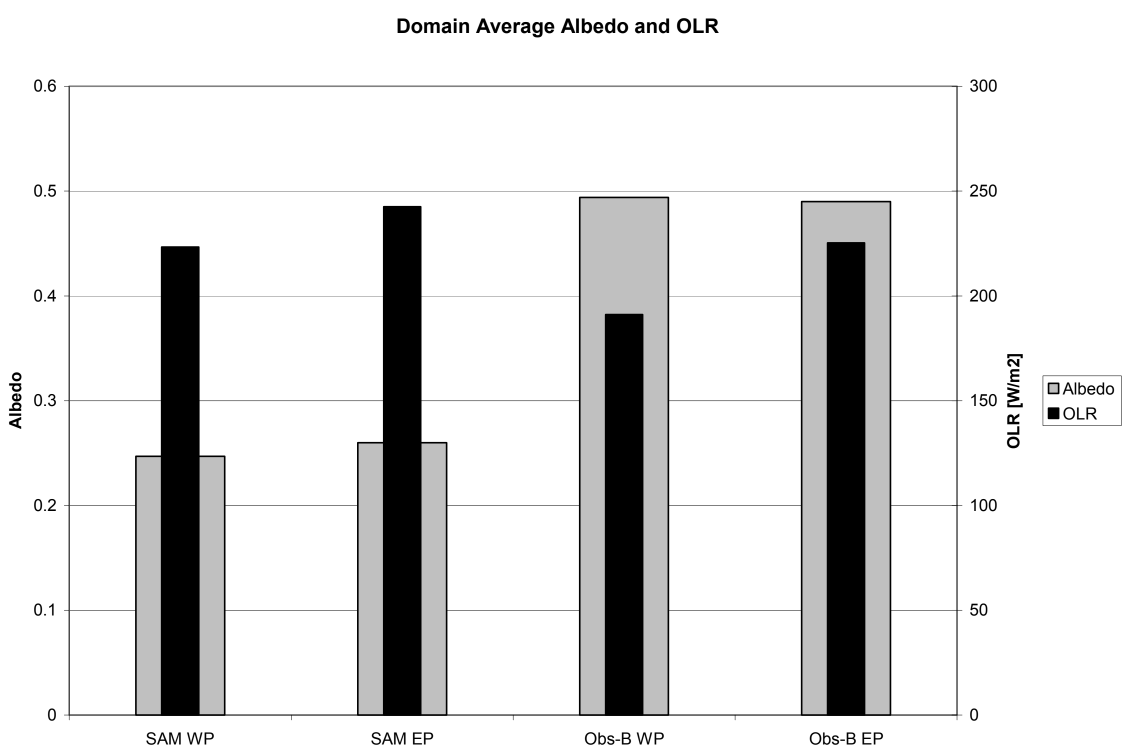

Figure 4-6: Comparison of domain averages of albedo and OLR in the 3-D SAM simulations and observations.

5. Mock-Walker Simulations

We wish to investigate whether changes to SAM can improve anvil cloud amount. However, performing many more 3-D runs would be computationally prohibitive. Two dimensional simulations have the advantage of using fewer computer resources, so they can be completed in a relatively short amount of time. If 2-D runs produce the same biases in anvil cloud amount as the 3-D runs, then a suite of 2-D runs can be used to test the sensitivity of anvil clouds to changes in the model. We examine this by performing BASE, a two dimensional SAM simulation described in Bretherton et al. (2006), which uses horizontal domain size and resolution of 4096 km and 2 km, respectively. SST is fixed as a sinusoidal function of distance, creating a warm pool in the center of the domain (figure 5-1). Consequently, the atmosphere organizes into a mock-Walker circulation, with convection mainly confined to the warm water (Grabowski et al. 2000; Bretherton et al. 2006). This setup is advantageous for studying convective cloud structures within the tropics because the primary source for high clouds is convection over the warm pool, although gravity waves could also be a source for high clouds elsewhere in the domain given sufficient moisture. Moreover, perhaps the greatest benefit of 2-D CRM mock-Walker simulations in climate research is in providing a way to study the interactions between cloud-radiative processes, mesoscale dynamics, and large-scale circulations within the same dynamical framework (Grabowski et al. 2000), albeit with only one horizontal dimension. Vertical resolution and the parameterizations for microphysics, radiation, and subgrid turbulent transport remain the same as in the 3-D runs. Again, there is no diurnal cycle of insolation. The nominal 6 second time step continues to be used, with radiation computed every 6 minutes. Although we do not apply large scale forcing to the atmosphere directly, a large scale circulation develops in response to the imposed SST gradient, allowing us to examine how high cloud properties depend upon precipitation rate in a realistic tropical circulation. Mean winds are nudged to zero on a 2 hour time scale to prevent the development of mean shear unrelated to the Walker circulation.

BASE is run for a total of 50 days. Model output consists of a series of instantaneous field snapshots, output eight times per day. In our analysis, 160 snapshots after RCE has been reached are used, which is 20 days worth of data. The same column-by-column algorithm from the 3-D runs is used to determine the abundance of thin, anvil, and thick clouds. In an attempt to match spatial scales with the data and 3-D runs, a horizontal block size of 128 km is used, and the cloud fractions from each block are averaged over 3 snapshots. This technique provides a large enough sample of data to facilitate comparisons with the data and the 3-D runs, with the time dimension standing as a proxy for spatial variability in the missing dimension. Again, we bin cloud fraction by percentile of rain rate.

BASE has too little anvil cloud amount to roughly the same degree as the 3-D runs, which can be clearly seen in both the domain average anvil to high thick cloud ratio (figure 5-2) and in the cloud fraction-rain rate composite (figure 5-3). Anvil cloud fraction seems to be more strongly dependent on rain rate, however. We suspect this may be related to the ability of the mock-Walker runs to represent a broader range of variability due to convective self-organization, which is not possible given the small domain with fixed SST and specified large scale-forcing of the 3-D runs. Anvil cloud fraction approaches 20 percent at the highest rain rate. Meanwhile, the relationship between thin cloud fraction and rain rate is less satisfying than in the 3-D runs, because thin cloud fraction increases with increasing rain rate rather than decreasing slightly. For rain rates less than 10 mm/day, thin cloud fraction is noticeably smaller than in the observations. The relationship between thin cloud fraction and rain rate seems erratic compared to the smoother relationships in the observations and the 3-D simulations. Although BASE shows a smooth relationship between thick cloud fraction and rain rate, thick cloud fraction becomes too large, nearly 2 times larger than in the 3-D runs at the highest rain rate.

Because BASE under-produces anvil cloud amount by roughly the same degree as the 3-D runs, we propose that the mock-Walker simulation is a useful tool for testing the sensitivity of anvil cloud in SAM to adjustments to the physics and resolution of the model. In this spirit, a suite of 2-D mock-Walker simulation experiments is performed using different adjustments to SAM, involving microphysics, resolution, and domain size. These adjustments will be described in detail in the next chapter.

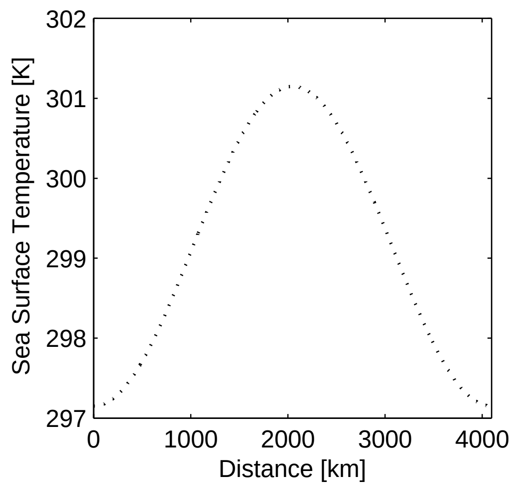

Figure 5-1: SST as function of distance in the 2-D mock-Walker simulations.

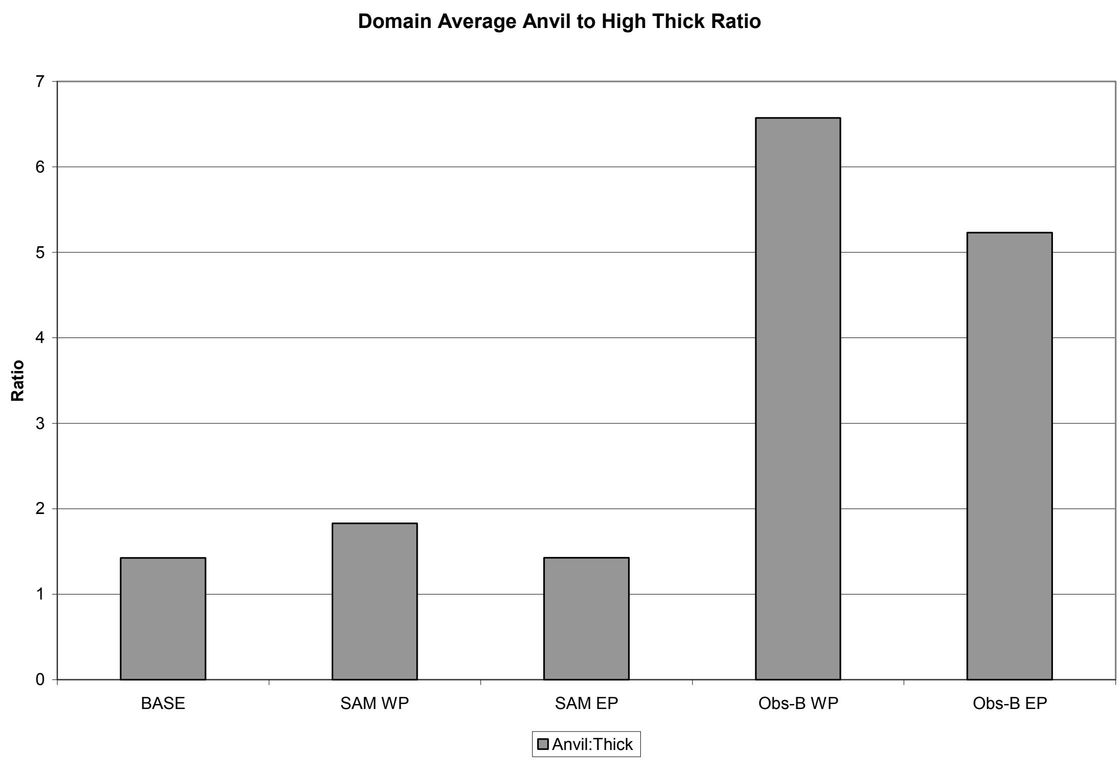

Figure 5-2: Domain average ratio of anvil to high thick cloud in 2-D BASE, the 3-D simulations, and the observations.

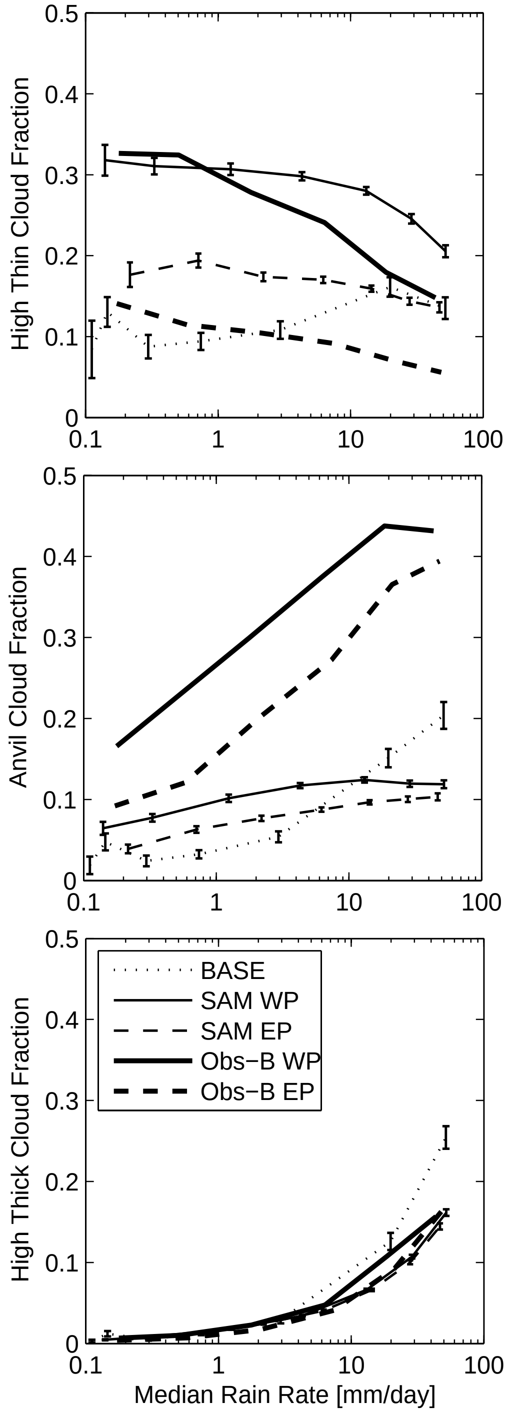

Figure 5-3: Cloud fraction rain rate composite comparing 2-D BASE, 3-D simulations, and observations.

6. 2-D Experiments

To determine how changes to the microphysics, resolution, and domain size of SAM affect anvil cloud abundance, we perform two dimensional mock-Walker sensitivity simulations, with the goal of improving the amount of anvil clouds produced by the model. The 2-D experiments are summarized in Table 6-1 and Table 6-2. Microphysics experiments include reduction of cloud ice fall speed, decreased and increased rates of autoconversion and accretion, and elimination of graupel. In horizontal resolution experiments, resolution is increased from the default value of 2 km to 1 km and 0.5 km. Vertical resolution experiments use an increased number of levels in the ice cloud layer. Finally, the experiments with domain size use a domain of 8192 km, twice as large as the default size. Detailed descriptions of all the 2-D experiments follow.

6.1 Microphysics

Changes to microphysics may be a plausible way to increase anvil cloud amount, because microphysical processes play a critical role in determining the amount of ice in the atmosphere. Krueger et al. (1995) used microphysical adjustments to increase the extent and ice water content of tropical anvil clouds in a CRM, by making changes to parameterizations of cloud ice growth, snow formation, and graupel. Also, microphysical processes may affect atmospheric circulation. By removing cold cloud processes from a 2-D CRM, Grabowski (2003a) demonstrates the resulting impact on atmospheric circulations produced by the warm-rain only version of the model, in which mesoscale convective systems have a shorter life cycle and reduced stratiform component. This suggests that cloud ice microphysics may play an important role in determining mesoscale circulations which may be important to the dynamics of anvil clouds.

6.1.1 Cloud Ice Fall Speed

In the microphysical parameterizations of SAM, cloud ice is allowed to fall slowly, although it is considered to be a non-precipitating hydrometeor species. The fall speed of cloud ice may affects the rate at which cloud material is lost due to sedimentation, if the clouds dissipate through evaporation as ice particles fall into sub-saturated air below the cloud base. Feingold et al. 1996 show that reduced drop fall speed increases drop in-cloud residence time in stratocumulus clouds, and this is probably generally applicable to other cloud systems too. Therefore, it seems plausible that anvil cloud amount may increase if cloud ice fall speed is reduced. In BASE (and also the 3-D simulations), cloud ice fall speed is parameterized as a function of ice water content, following Heymsfield (2003):

$$v_{t_{ice}} = 165(IWC)^{0.24},$$

with $v_{t_{ice}}$ in cm/s and IWC in g/m^3. In VTHALF, the cloud ice fall speed computed in the preceding formula is decreased by a factor of two (figure 6-1).

VTHALF fails to improve the relationship between anvil cloud fraction and rain rate (figure 6-2). Although anvil cloud fraction increases noticeably, it becomes nearly independent of rain rate and remains nearly 20 percent lower than observations at the highest rain rates. Thin cloud fraction also increases in VTHALF, displaying a slight decreasing trend with increasing rain rate. Also, high thick cloud fraction becomes undesirably larger than in BASE at all rain rates. These results seem to suggest that slowing cloud ice fall speed causes all clouds to last longer, so this is not an effective strategy for improving the relationship between anvil cloud fraction and rain rate.

6.1.2 Autoconversion and Accretion

Autoconversion and accretion are processes that possibly affect cloud lifetime. The rate of autoconversion determines how quickly cloud liquid or ice is converted to precipitation by coalescence or aggregation, respectively. By reducing this rate, the onset of precipitation may be delayed, prolonging cloud lifetime. Meanwhile, the accretion rate controls the growth of precipitating condensate through the collection of non-precipitating condensate. A decreased accretion rate might reduce the size of precipitating hydrometeors, possibly increasing cloud lifetime by slowing hydrometeor fall speed. To examine the effect of changing the rates of autoconversion and accretion, AAHALF, AATWO and AATEN multiply the default rates of autoconversion and accretion for both liquid and ice by factors of 0.5, 2 and 10, respectively.

Theses experiments have little effect on anvil clouds. The relationship between anvil fraction and rain rate in AAHALF, AATWO, and AATEN is nearly identical to the relationship found in BASE (figure 6-3). However, these runs do display some differences in thin cloud fraction, with AATWO producing nearly twice as much thin cloud as AAHALF at the highest rain rates. Thin cloud fraction increases noticeably in both AATWO and AATEN after rain rate exceeds 1 mm/day, behavior in disagreement with the observations which tend toward a decrease in thin cloud fraction with increasing rain rate. Interestingly, AATWO and AATEN produce thick cloud fractions that compare well with observations at all rain rates, a noteworthy improvement from BASE. In contrast, AAHALF noticeably overproduces high thick clouds, a bias which becomes quite large at rain rates greater than 10 mm/day.

To better understand how these experiments alter the amount of high thick cloud in the 2-D simulations, it is necessary to determine whether changes to the rates for liquid or to the rates for ice are the primary cause for reduced high cloud fractions in AATWO and AATEN. Therefore, HALFICE and TWOICE multiply the rates of only ice autoconversion and accretion by factors of 0.5 and 2, respectively. The results of these runs are negligibly different than BASE (figure 6-4), so we can conclude that the behavior of high cloud fraction witnessed in AAHALF, AATWO, and AATEN is due solely to changes in the liquid autoconversion and accretion rates. Increased rates of autoconversion and accretion in AATWO and AATEN probably increase precipitation efficiency in convective cores. As a result, high thick cloud fraction decreases because cloud liquid water below the freezing level is rained out.

6.1.3 Graupel

Graupel forms when ice particles accrete cloud liquid. If ice particles are precipitating inside convective cores, a significant amount of liquid water located below the freezing level may be lost through the formation of graupel. The increase in graupel at the expense of cloud liquid within convective cores seemingly reduces the amount of water that can be lofted upward to higher levels where it could possibly detrain in the formation of anvil clouds. Therefore, reducing the amount of graupel in SAM may increase the amount of anvil clouds produced. NOGRAU eliminates graupel as a precipitating hydrometeor species.

Like most other experiments with microphysics, NOGRAU does not improve the relationship between anvil cloud fraction and rain rate (figure 6-5). Also, high thin cloud amount does not change substantially. It is somewhat surprising that high thick cloud fraction remains similar to BASE, because the lack of graupel suggests an increase in the amount of cloud liquid water inside convective cores. As the results of AAHALF demonstrate, increased amounts of liquid water in convective cores tend to increase high thick cloud fraction. NOGRAU shows only a very slight increase in thick cloud fraction at higher rain rates.

6.2 Resolution

Increased resolution may be necessary if physical processes important to anvil clouds occur on scales finer than the default resolution of the model. To investigate whether higher horizontal resolution than the default 2 km may increase anvil amount, we perform HORRES 1 and HORRES 0.5 which use horizontal resolutions of 1 km and 0.5 km, respectively. Also, it is useful to investigate the sensitivity of anvil cloud amount to changes in the vertical resolution of SAM. VERTRES increases vertical resolution by using 200 m spacing between levels throughout the ice cloud layer.

Changes in resolution do not improve anvil cloud amount. The experiments with higher horizontal resolution do not significantly affect the relationship between anvil cloud fraction and rain rate (figure 6-6). Also, thin cloud fraction changes only slightly in HORRES 1 and HORRES 0.5. Thick cloud fraction remains quite similar to base too. Likewise, increased vertical resolution does not yield favorable changes to the relationship between anvil cloud fraction and rain rate (figure 6-7). In fact, anvil cloud fraction in VERTRES *decreases* slightly at higher rain rates. Fractions of thin and thick clouds in VERTRES differ little from BASE, although the relationship between thin cloud fraction and rain rate becomes smoother.

6.3 Domain Size

A larger domain contains a more realistic SST gradient and gives convection more space to organize. If these changes produce more realistic convective systems, better cloud structures may result, possibly containing more anvil cloud. DOMAIN1 doubles the size of the horizontal domain to 8192 km, creating a warm pool twice as large as the one that exists when using the default domain size. Maximum and minimum SSTs remain the same as in BASE. Also, horizontal and vertical resolutions remain at their default values used in BASE. To investigate whether the larger domain might provide a more favorable platform for testing microphysical adjustments, we perform DOMAIN2, which uses the double domain and halved terminal velocity of ice.

Increasing the domain size alone does not improve anvil cloud amount appreciably, but a larger domain with decreased terminal velocity shows somewhat favorable results. The larger horizontal domain in DOMAIN1 does not change anvil cloud amount significantly (figure 6-8). However, the relationship between anvil cloud fraction and rain rate is stronger. Thin cloud amount produced by DOMAIN1 decreases from the base run, but the relationship between thin cloud fraction and rain rate is smoother. The amount of thick clouds produced by DOMAIN1 is excessive. Although still producing fewer anvils than observations, DOMAIN2 improves anvil cloud amount substantially compared with BASE. The relationship between thin cloud fraction and rain rate is also slightly better than in BASE. Unfortunately, excess production of thick clouds is a persistent problem in both runs with increased domain size.

Table 6-1: Descriptions of 2-D SAM experiments.

Run	Description
BASE	Default 2-D simulation
VTHALF	Reduce cloud ice fall speed
AAHALF	Decrease rates of autoconversion and accretion for liquid and ice by factor of 2
AATWO	Increase rates of autoconversion and accretion for liquid and ice by factor of 2
AATEN	Increase rates of autoconversion and accretion for liquid and ice by factor of 10
HALFICE	Decrease rates of autoconversion and accretion for ice only by factor of 2
TWOICE	Increase rates of autoconversion and accretion for ice only by factor of 2
NOGRAU	Eliminate graupel as a hydrometeor species
HORRES 1	Increase horizontal resolution to 1 km
HORRES 0.5	Increase horizontal resolution to 0.5 km
VERTRES	Use 200 m horizontal resolution throughout the ice cloud layer
DOMAIN1	Double size of horizontal domain
DOMAIN2	Double size of horizontal domain and reduce cloud ice fall speed

Table 6-2: Summary of 2-D SAM experiments.

Run	**Domain Size**	**Horizontal Res**	**Vertical Res**	**Halved V_t**
BASE	4096 km	2 km	Default	No
VTHALF	4096 km	2 km	Default	Yes
AAHALF	4096 km	2 km	Default	No
AATWO	4096 km	2 km	Default	No
AATEN	4096 km	2 km	Default	No
HALFICE	4096 km	2 km	Default	No
TWOICE	4096 km	2 km	Default	No
NOGRAU	4096 km	2 km	Default	No
HORRES 1	4096 km	1 km	Default	No
HORRES 0.5	4096 km	0.5 km	Default	No
VERTRES	4096 km	2 km	Increased	No
DOMAIN1	8192 km	2 km	Default	No
DOMAIN2	8192 km	2 km	Default	Yes

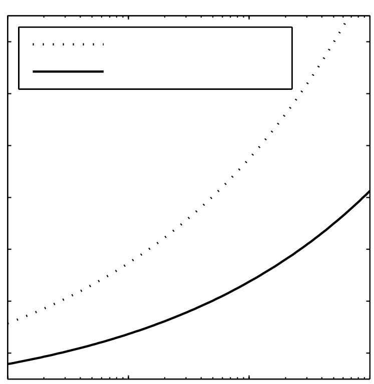

Figure 6-1: Comparison of terminal velocity parameterizations used in BASE, following Heymsfield (2003), and VTHALF.

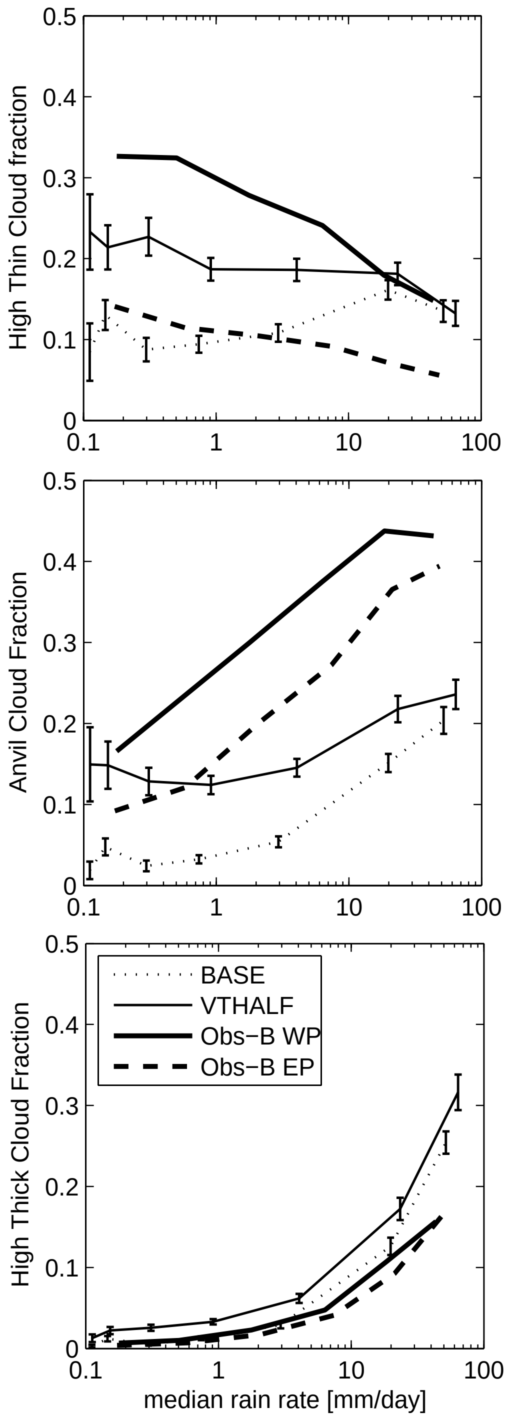

Figure 6-2: Comparing the results of VTHALF to the original fall speed parameterization in BASE.

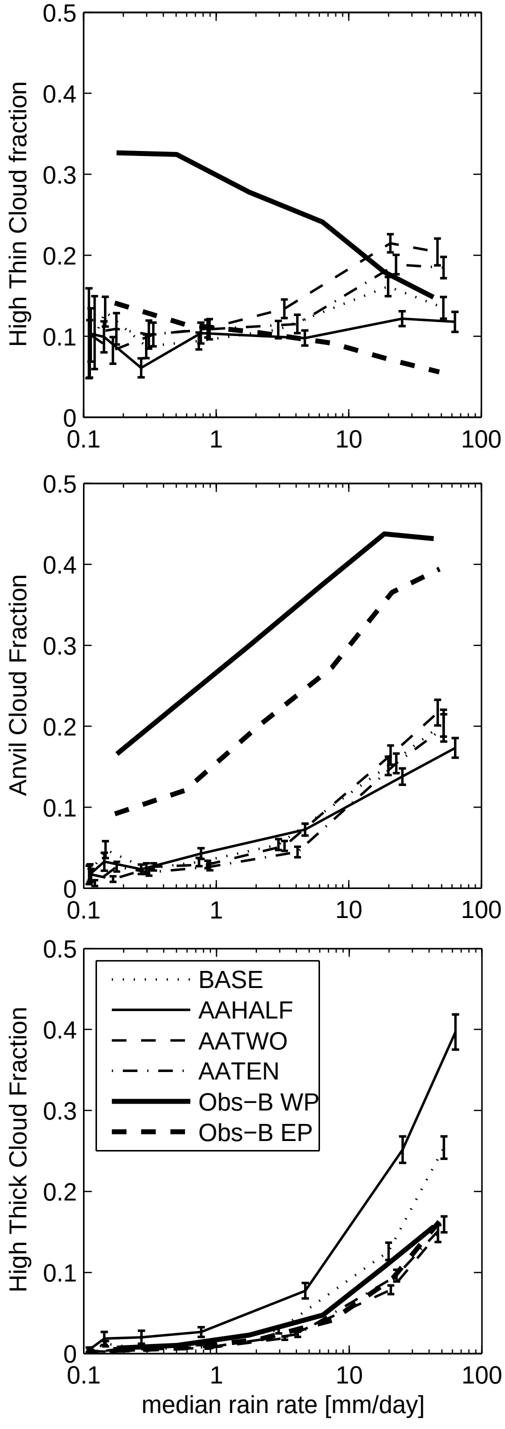

Figure 6-3: Results of changes to autoconversion and accretion rates for both liquid and ice.

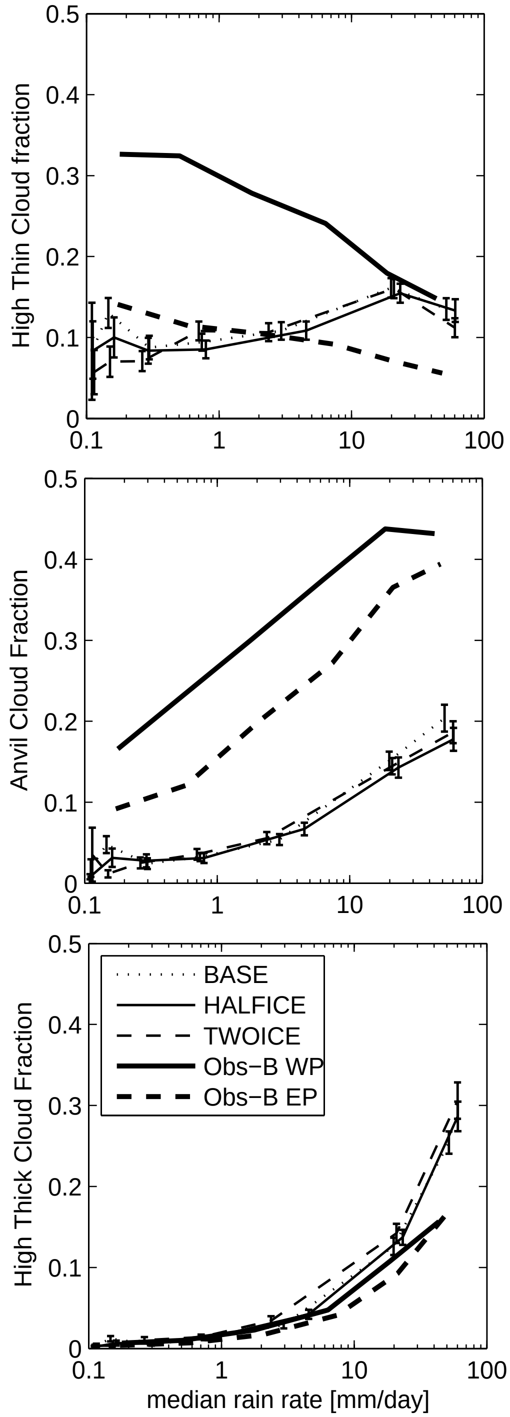

Figure 6-4: Results of changes to autoconversion and accretion rates of ice only.

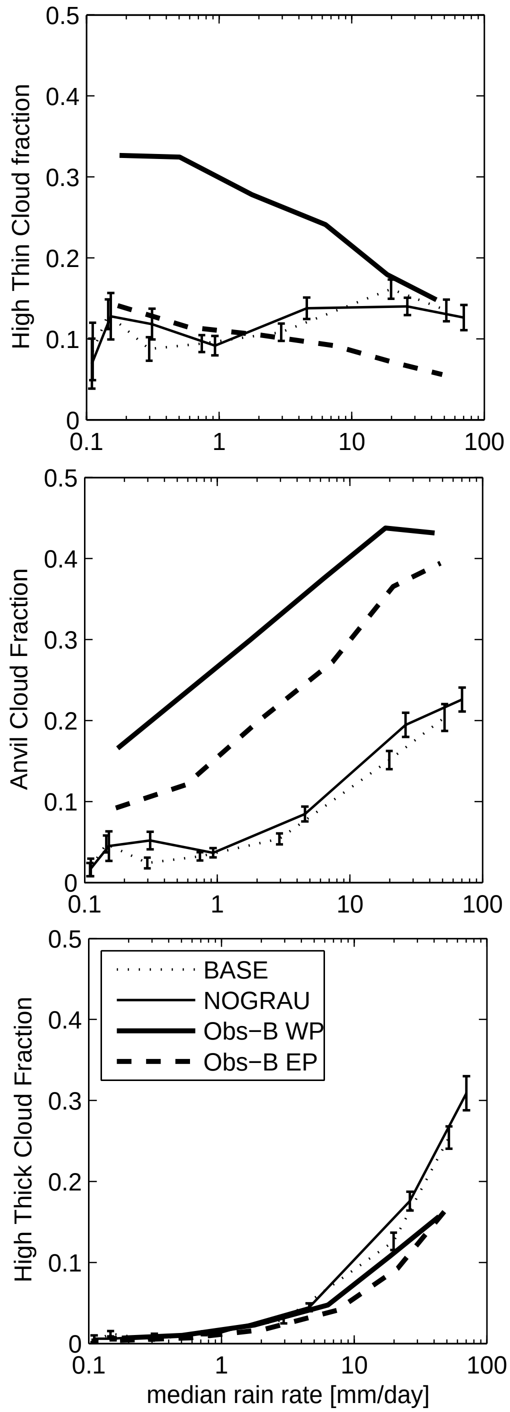

Figure 6-5: Comparison of 2-D simulation without graupel to BASE.

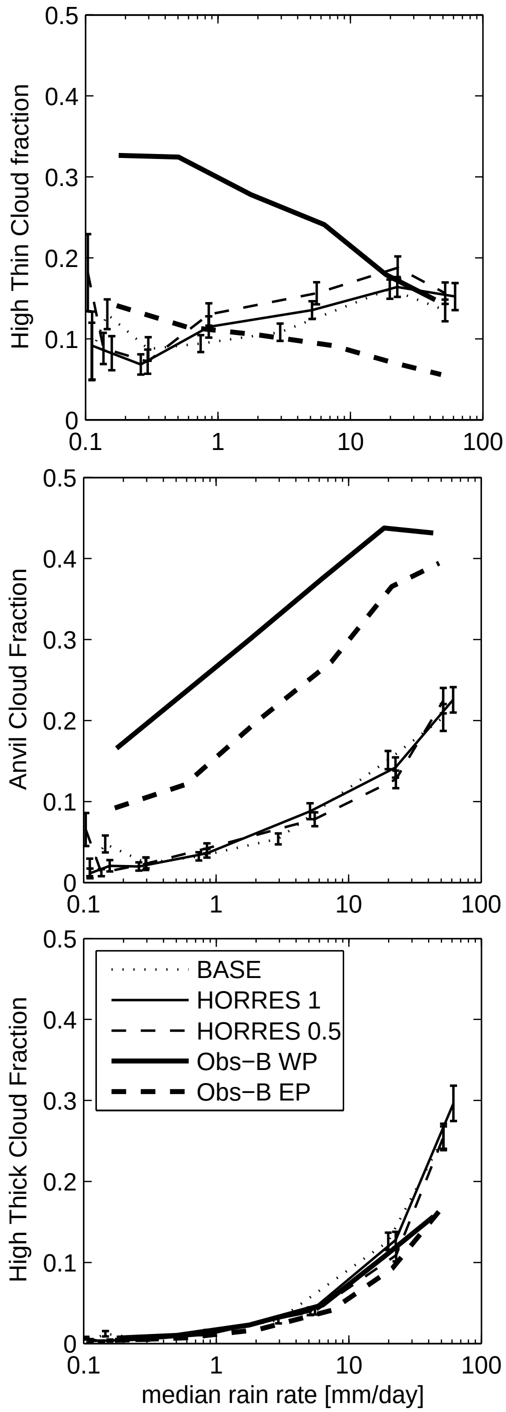

Figure 6-6: Experiments with 1 km and 0.5 km horizontal resolution.

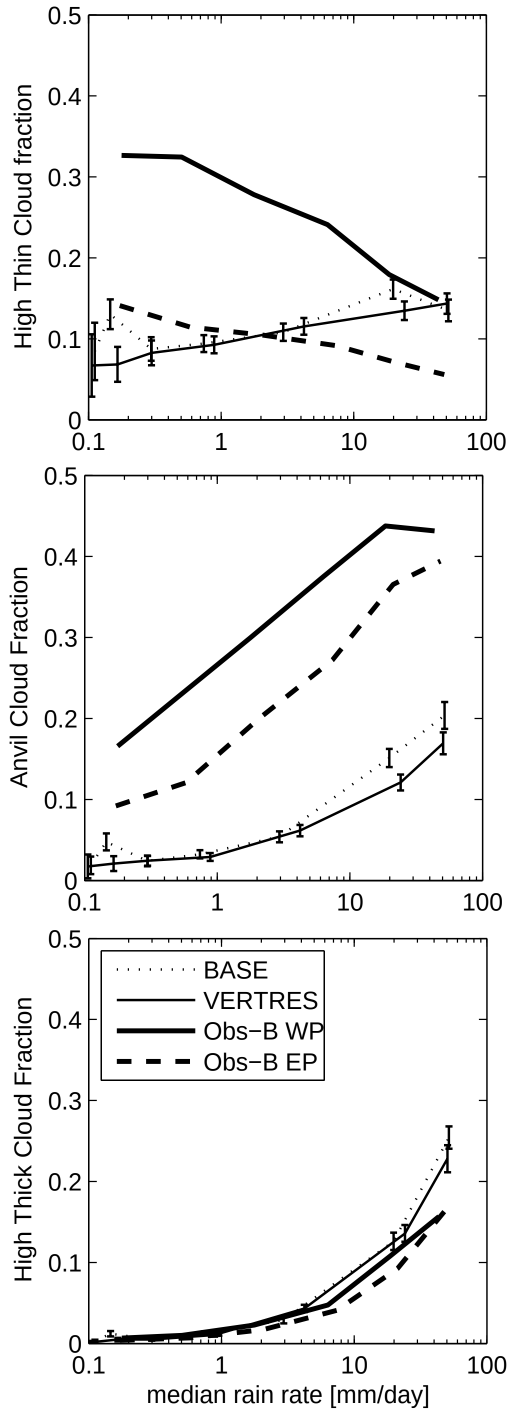

Figure 6-7: Experiment with increased vertical resolution.

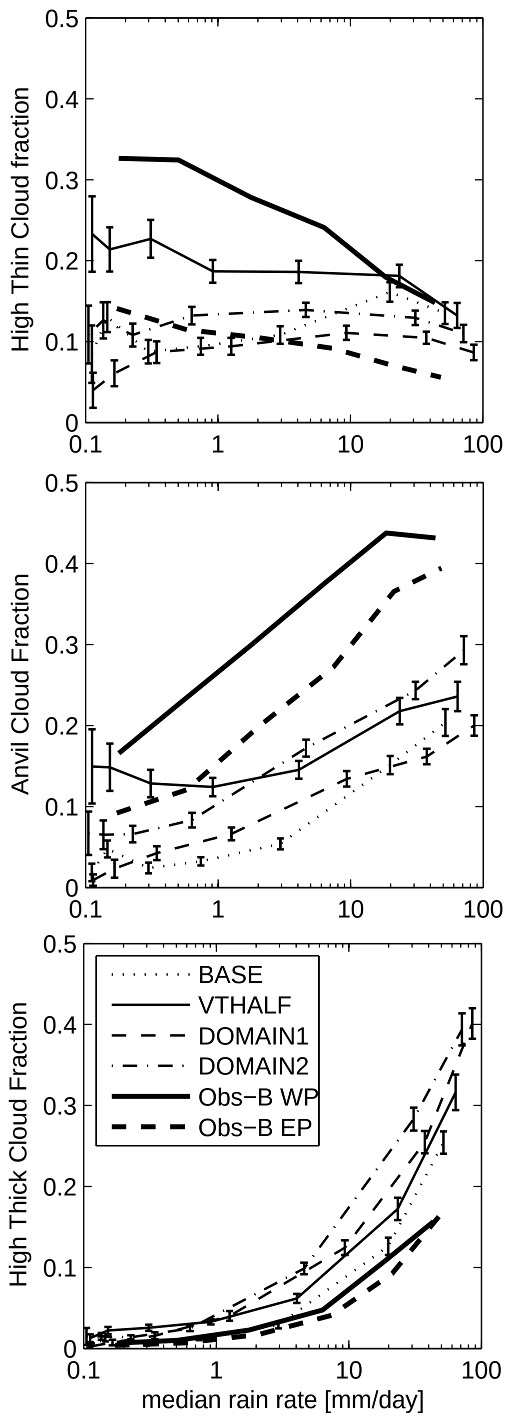

Figure 6-8: DOMAIN2 has the same effect as VTHALF, but it produces a better relationship between anvil cloud fraction and rain rate.

7. Discussion

Because the amount of anvil clouds produced by the 3-D simulations is small, these runs fail to produce a realistic high cloud distribution. The lack of anvil clouds is troubling, as it leads to biases in TOA radiative fluxes. Consequently, it is important to explain the reasons why SAM fails to produce a substantial amount of anvil clouds. The nudging of the mean horizontal wind profile in the 3-D runs is one possible factor limiting anvil cloud development. In nature, anvil cloud coverage in the tropics is probably most extensive when anvil clouds form in association with large convective super clusters, because of the large extent of anvil clouds relative to convective cores (Leary and Houze 1980) and the long lifetime and spatial coverage of super clusters (Mapes and Houze 1993; Chen et al. 1996). To generate super clusters, organization of convective systems through self-aggregation may be necessary in the model. Nudging of the horizontal winds in the simulations creates persistent vertical shear that may suppress the development of super clusters. Indeed, Bretherton et al. (2005) show that a shear free environment is needed for self-aggregation to proceed in SAM. Their findings also suggest that the domain size of 256 by 256 km used in our 3-D simulations may be too small for self-aggregation to occur. In the 2-D simulations, the imposed SST gradient may encourage a small amount of self-aggregation to occur over the warm pool, which may explain why anvil cloud fraction increases more noticeably with rain rate in BASE than in the 3-D simulations. Still, self-aggregation is limited by nudging of the horizontal winds, and the lack of a second horizontal dimension is probably an additional hindrance to the development of super clusters. In our own analysis of the self-aggregation experiments of Bretherton et al. (2005), we show that anvil cloud fraction increases substantially at all rain rates during the mature stage (days 46-50) of self-aggregation compared to the earlier stages (figure 7-1) but does not show the observed relation to rain rate. Moreover, too much high thick cloud is produced at all rain rates, so the domain average ratio of anvil cloud to high thick cloud remains much smaller than observations (figure 7-2), suggesting that the inclusion of self-aggregating systems in the 3-D simulations will do little to improve the TOA energy budget.

If self-aggregation does not improve the simulation of anvil clouds in SAM, then other changes are necessary to produce improvements. Unfortunately, our 2-D mock-Walker simulations show that SAM is rather insensitive to changes in physics, resolution, and domain size. Experiments with microphysics in the 2-D simulations fail to improve the relationship between anvil cloud fraction and rain rate. Reducing cloud ice fall speed increases anvil cloud fraction. Unfortunately, this does not improve the high cloud distribution, because reduced cloud ice fall speed simultaneously increases the amount of all three categories of high cloud. The experiments with autoconversion and accretion do not improve anvil cloud amount. However, they suggest that increased autoconversion and accretion rates for cloud liquid can reduce an excess of high thick clouds which is persistent in the 2-D simulations. Results of the experiments with resolution and domain size were not particularly encouraging. In their 3-D KWAJEX simulations, Blossey et al. (2007) also find SAM to be insensitive to the type of adjustments that we apply in our 2-D experiments, with changes to microphysical parameterizations doing little to reduce persistent biases in albedo and OLR. They also found little sensitivity to changes in domain size and horizontal resolution. Pauluis and Garner (2006) show that, at horizontal resolutions finer than 4 km, further increases in CRM resolution do not affect the amount of simulated high cloud.

A few other possibilities exist that may explain why SAM produces a low amount of anvil clouds. Perhaps the model does not produce enough cloud ice, reducing the probability of forming anvil clouds. In this scenario, convective cores would be composed mainly of cloud liquid rather than ice. The 2-D experiments lend some support to this possibility, as increased rates of autoconversion and accretion of liquid water are effective at decreasing high thick cloud fraction. To form anvil clouds, detrainment of cloud ice from convective cores is necessary. Perhaps substantial detrainment does not occur in SAM, in which case cloud ice would tend to remain in columns containing convective cores rather than spreading as anvil cloud. Blossey et al. (2007) suggest that SAM produces precipitation too efficiently in a few highly convective columns, which might limit the amount of cloud ice that is detrained. Ultimately, a significant increase of vertical resolution might be needed to resolve stratiform convection within anvil clouds. Although higher vertical resolution does not improve anvil cloud amount in the 2-D experiments, perhaps the increase from 400 to 200 m resolution in VERTRES is insignificant. Anvil cloud abundance may only improve if extremely fine vertical resolution is used, perhaps on the order of tens of meters. Unfortunately, this would be very computationally expensive.

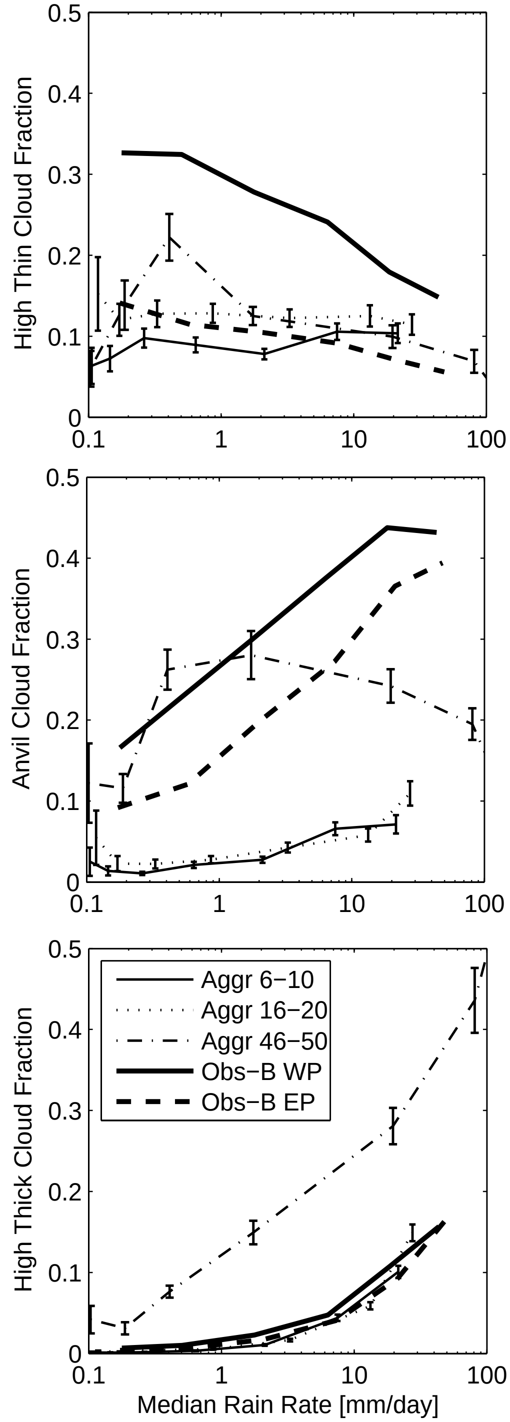

Figure 7-1: Cloud fraction rain rate composites for days 6-10, 16-20, and 46-50 (mature stage) compared with observations.

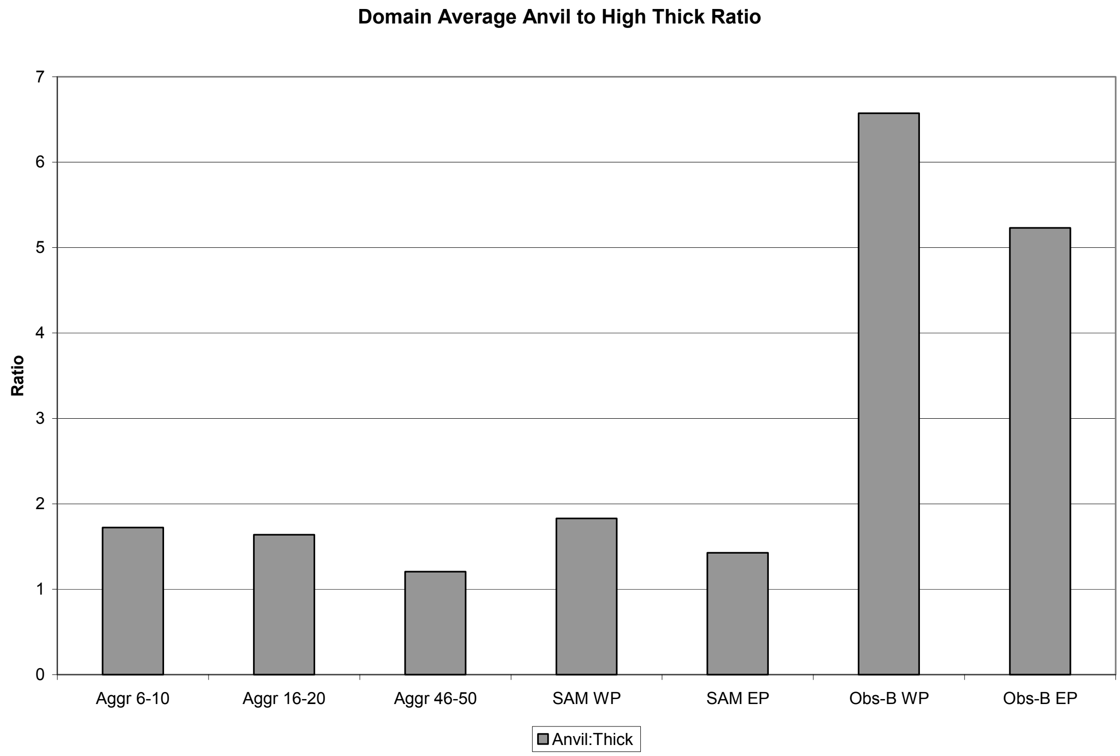

Figure 7-2: Domain average anvil to high thick cloud fraction in the SAM 3-D experiments with self-aggregation, our 3-D SAM simulations, and observations.

8. Conclusions/Future Work

The three dimensional SAM simulations described here do not produce the same convective cloud distribution observed by satellites. The amount of high thick clouds per unit of precipitation in the simulations agrees well with the observations, and the amount of high thin cloud is at least roughly similar to observations. However, the amount of anvil clouds is remarkably under-predicted, leading to biases in albedo and OLR. Two-dimensional simulations are used to test ideas that might improve anvil cloud amount. Unfortunately, none of the ideas tested in the 2-D experiments were very effective at improving the relationship of anvil cloud to precipitation. To test whether self-aggregation may improve the distribution of high clouds in SAM, we show that 3-D self-aggregation experiments by Bretherton et al. (2005) do not greatly improve the domain average ratio of anvil cloud to high thick cloud. These results may suggest that simple RCE experiments run on small domains may not capture the true effects of clouds on the radiation budget and that the correct cloud radiative properties can only be obtained if the clouds are placed in the context of their larger scale meteorological environment.

Continued work is necessary to improve anvil cloud representation in the SAM model, and such effort is worthwhile because it may improve the representation of TOA radiative fluxes, by producing a more realistic convective cloud distribution. Perhaps self-aggregation combined with microphysical adjustments can help. In particular, increasing the rates of autoconversion and accretion of liquid water might help improve the ratio of anvil cloud to high thick cloud, by reducing the persistent excess of high thick cloud in the self-aggregation runs of Bretherton et al. (2005). If this does not work, further experiments will be necessary to test whether resolving stratiform convection can increase anvil cloud abundance. A small domain run with 100 m vertical resolution may be a good starting point.

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