Testing the Fixed Anvil Temperature Hypothesis in a Cloud-Resolving Model

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ABSTRACT

Using cloud-resolving simulations of tropical radiative–convective equilibrium, it is shown that the anvil temperature changes by less than 0.5 K with a 2-K change in SST, lending support to the fixed anvil temperature (FAT) hypothesis. The results suggest that for plausible ozone profiles, a decrease in the air's emission capability instead of ozone heating shall remain the control on the detrainment level, and the FAT hypothesis should hold. The anvil temperature also remains unchanged with other changes in the system such as the doubled CO_2 mixing ratio, doubled stratospheric water vapor concentration, and dynamical cooling due to the Brewer–Dobson circulations. The results are robust when a different microphysics scheme is used.

1. Introduction

Tropical anvil clouds are observed to exert large cloud radiative forcing that is of the opposite sign in the longwave (LW) and shortwave (SW) (Hartmann et al. 1992). In the current climate, the LW and SW effects largely cancel at the top of the atmosphere (TOA; Ramanathan et al. 1989). From the TOA energy budget point of view, it is important to understand whether or not this cancellation will hold under future climatic conditions (Kiehl 1994; Hartmann et al. 2001a). The radiative importance of these anvil clouds also extends beyond their TOA effects because they tend to cool the surface and heat the atmosphere. Such a differential heating enhances the atmospheric static stability.

Until recently, there have been few theories that predict how the anvils would respond and feed back to climate change. In a recent paper, Hartmann and Larson (2002, hereafter HL02) argued that the temperature at which tropical convective anvils detrain should be insensitive to climate change. This will be referred to as the fixed anvil temperature (FAT) hypothesis.

Since the updrafts of deep convection are concentrated in small areas and convective heating of the atmosphere is mostly realized through adiabatic heating by compensating subsidence, there exists a dominant balance between clear-sky radiative cooling Q_{clr} (negative for cooling) and subsidence heating in the Tropics; that is, we have the diagnostic equation

$$\omega \frac{d\theta}{dp} = \frac{\theta}{T} Q_{clr}, \qquad (1)$$

where θ is potential temperature, p is pressure, ω is the pressure velocity, and T is temperature. We shall define $\Gamma \equiv d\theta/dp$ as a measure of the stratification. The anvil itself induces differential radiative heating (positive at the base and negative at the top), which can be significant when the anvil fraction is large. However, this differential radiative heating mostly drives turbulence within the anvil cloud, instead of being compensated by large-scale subsidence, and is therefore neglected in Eq. (1). The divergence field implied by the subsidence rates is

$$\frac{d\omega}{dp} = \frac{d}{dp}\left(\frac{\theta Q_{clr}}{T\Gamma}\right) \qquad (2)$$

and is expected to largely control the detrainment level of tropical anvils.

The deep Tropics are different from the extratropics in that the radiative relaxation rate declines significantly before the tropical tropopause is reached be-

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cause the very cold air in the upper tropical troposphere contains little water vapor (Hartmann et al. 2001b). HL02 argued that it is the rapid decrease in clear-sky radiative cooling rates with height/pressure that is important in Eq. (2). They then argued that the radiative emission capability of a noncloudy upper-tropospheric air parcel is most strongly related to its temperature. This is because of the strong temperature dependence of the saturation water vapor pressure in the Clausius–Clapeyron relation and the fact that water vapor is the main emitter in the upper troposphere. Because of these, they reasoned, the temperature at the level where clear-sky radiative cooling rates rapidly decrease with height, and hence that of the anvils, should remain approximately the same as the surface temperature changes. As the FAT hypothesis attempts to relate the emission temperature of tropical anvils to fundamental constraints such as the Clausius–Clapeyron relation and the longwave emission lines of water vapor, it can potentially lend significant predictive power to studies of cloud–climate feedbacks.

Complementary to an effort to test this hypothesis observationally (Xu et al. 2007), we will in this study focus on a numerical modeling approach. In HL02, the FAT hypothesis was tested using mesoscale models where convection is parameterized. It is desirable to test the hypothesis in a cloud-resolving model (CRM). A CRM has its own uncertainties, particularly with respect to the microphysics, which has to be parameterized. By explicitly including cumulus-scale motion, however, a CRM appears to better incorporate most of the relevant physical processes in the present problem. We shall use an atmosphere in radiative–convective equilibrium (RCE) as a first approximation to the tropical atmosphere.

Three-dimensional CRM studies on the sensitivity of tropical convection in RCE to SST variations have been conducted (Tompkins and Craig 1999). While their main interest was not on the anvil temperature, based on their results, these authors suggested an increase in the anvil temperature with an increase in SST. However, the resolution in the upper troposphere is quite coarse ($\sim$1 km) in that study. This limits their ability to accurately quantify the anvil temperature changes, as recognized by Tompkins and Craig (1999). To adequately test the FAT hypothesis, finer vertical resolution in the upper troposphere is needed.

2. Model and experimental setup

We use the System for Atmospheric Modeling (SAM) version 6.3, which is a new version of the Colorado State University Large Eddy Simulation/Cloud Resolving Model (Khairoutdinov and Randall 2003).

The model uses the anelastic equations of motion with bulk microphysics. The prognostic thermodynamic variables are the liquid water static energy, total non-precipitating water, and total precipitating water. The radiation schemes are those of the National Center for Atmospheric Research (NCAR) Community Climate Model version 3 (CCM3; Kiehl et al. 1998). Readers are referred to Khairoutdinov and Randall (2003) for details about the model. For this study, we use a simple Smagorinsky-type scheme for the effect of subgrid-scale turbulence. We have removed the diurnal cycle by fixing the solar zenith angle at 50.5° and adjusting the solar constant to yield a constant solar input of 414 W m^{-2}. The surface fluxes are computed using the Monin–Obukhov similarity theory.

For the experiments to be presented, we use a doubly periodic domain of 64 km $\times$ 64 km with the model top placed near 40 km. The horizontal grid size is uniformly 1 km. A total of 96 vertical layers are used. The vertical grid size increases gradually from 75 m near the surface to 300 m at $\sim$5 km. It is then uniformly 300 m up to 20 km, where it gradually increases to 1 km. A wave-absorbing layer was placed in the upper third of the domain. As discussed in Kuang and Bretherton (2004), gravity waves excited in the upper troposphere become increasingly compressed in the vertical as they propagate upward into the lower stratosphere because of the increasing stratification. A much finer vertical grid is needed in the lower stratosphere to avoid the numerical dissipation of gravity waves, which was found to be important for the heat budget near the cold point tropopause. For the present problem, however, its effect is small so a uniform grid in this region is used to reduce the computational costs. We use a fixed ozone profile taken from the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE; Webster and Lukas 1992). All experiments are run for 75 days. It takes about 35 days for the model to reach radiative–convective equilibrium, so results averaged for the last 40 days are presented. All variables are sampled every 10 min.

3. Results

In Fig. 1, we show the domain-averaged temperature and cloud fraction as functions of height for a set of RCE experiments with SSTs of 32.5°, 30.5°, 28.5°, and 26.5°C. A grid point is identified as cloudy when its cloud condensate specific humidity is greater than 10^{-5} kg kg^{-1}. The relative error of the 40-day mean cloud fraction due to fluctuations of the cloud field is less than 5% for the anvil region. In Fig. 2, normalized cloud fraction and divergence [diagnosed from Eq. (2)] are shown as functions of temperature.
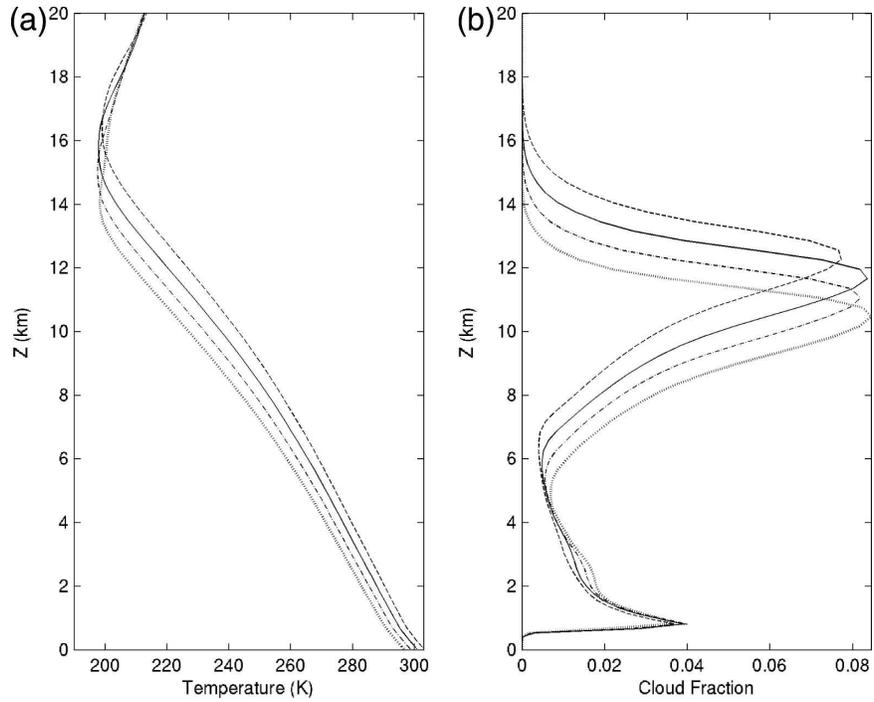
FIG. 1. RCE profiles of (a) temperature and (b) cloud fraction for SSTs of 32.5° (dashed), 30.5° (solid), 28.5° (dashed–dotted), and 26.5°C (dotted).
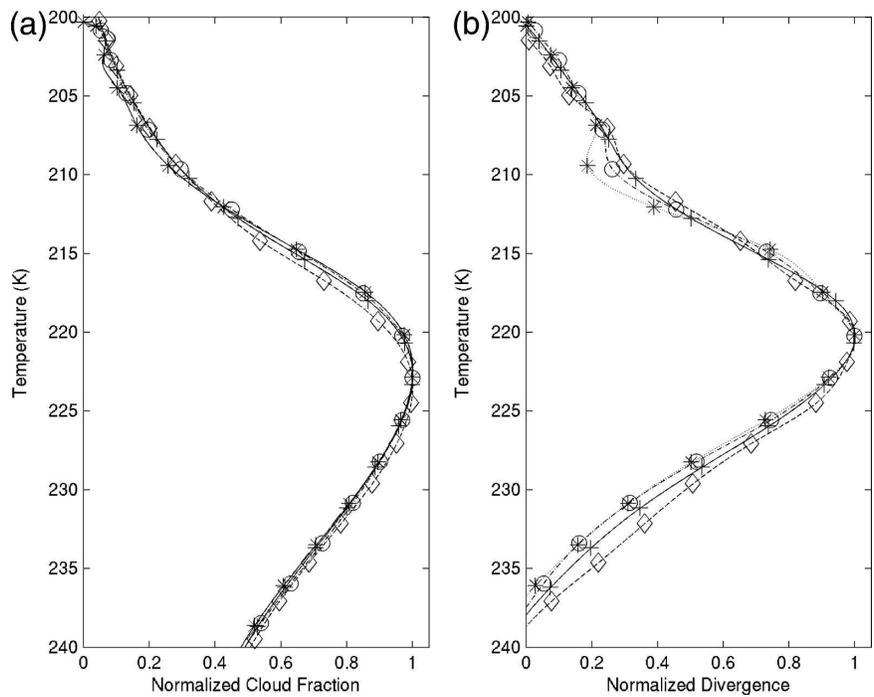

FIG. 2. Normalized (a) cloud fraction and (b) divergence estimated from Eq. (1) as functions of temperature for SSTs of 32.5° (dashed, diamond), 30.5° (solid, +), 28.5° (dashed–dotted, circle), and 26.5°C (dotted, *).
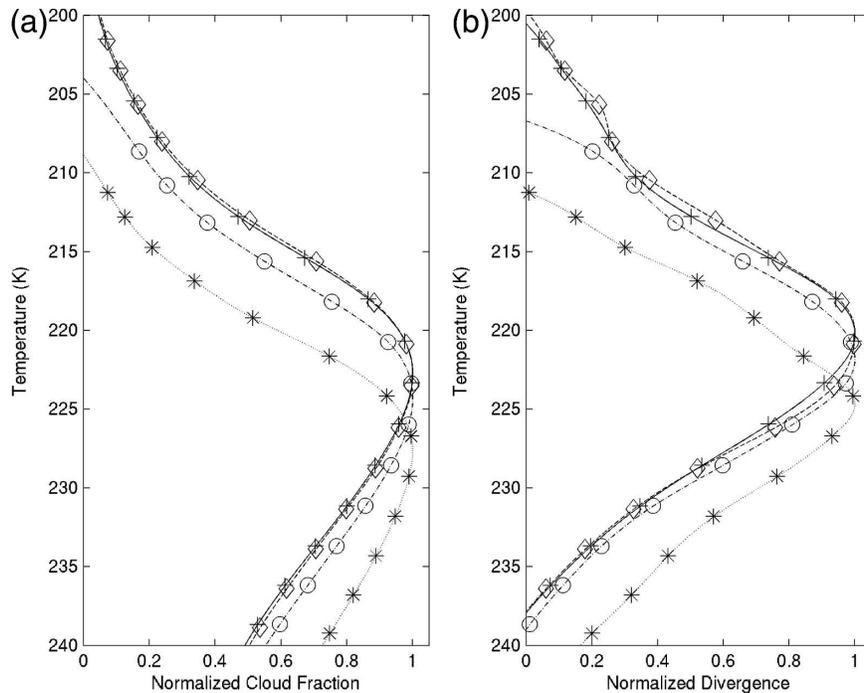
FIG. 3. Normalized (a) cloud fraction and (b) divergence as functions of temperature with the ozone profile shifted by +8 km (diamond), 0 km (+), −4 km (circle), and −12 km (*). The SST is 30.5°C.

The results on anvil temperature strongly support the FAT hypothesis. The anvil temperature changes by less than 0.5 K (compared to ∼6-K increases in upper-tropospheric temperature) for a 2-K increase in the SST. The divergence diagnosed from Eq. (2) also appears to be a good predictor for the anvil detrainment level.

While Eq. (1) is a very useful diagnostic relation, it is also instructive to have a prognostic view on how the balance is established. More specifically, as individual convective parcels shall detrain near their levels of neutral buoyancy (LNB), how are they connected to an increase in the radiative relaxation time scale, the key component that is linked to water vapor and hence temperature in the FAT hypothesis? To see this, let us consider a thought experiment where we have a mass flux distribution of $M(\theta_e)$ for the ensemble of parcels arriving at the bottom of the detrainment region (say $T = 240$ K). We shall consider $M(\theta_e)$ as controlled by processes in the boundary layer and the bulk troposphere and treat it as external to our discussion. We further simplify the radiative processes in the detrainment region as relaxation processes toward a radiative equilibrium temperature profile with a relaxation time-scale profile, both treated as given. (In reality, radiative transfer is a global problem and the relaxation cannot be treated as local, and the boundary layer is not inde-

pendent of convective processes in the free troposphere. This does not affect the current argument, however.) With these specifications, the problem is closed. We can assume that these parcels adapt to their LNB, a simplistic but reasonable view of the detrainment process (Folkins 2002). This will adjust the mass between constant θ surfaces [i.e., $\theta(p)$ profile until Eq. (1) is satisfied]. The final solution depends on the prescribed profiles of radiative equilibrium temperature and relaxation time scale. In a region of rapid increase in the radiative relaxation time scale, it (as opposed to the radiative equilibrium profile) will have the dominant effect on the final equilibrium temperature, lapse rate, and radiative cooling profiles, and hence the detrainment level.

It is also possible to be in a regime where a rapid increase in the radiative equilibrium profile controls the detrainment so that the argument of HL02 no longer applies. For illustrative purposes, we have conducted a set of hypothetical experiments using the fixed ozone profile from the control run, except shifted downward/ upward by 4, 8, and 12 km, similar to that of Thuburn and Craig (2002). Each ozone profile is scaled by a constant to yield the same column ozone amount. The results (shown in Fig. 3) indicate that with an ozone profile shifted upward so that there is a smaller influence by ozone heating, the anvil temperature remains
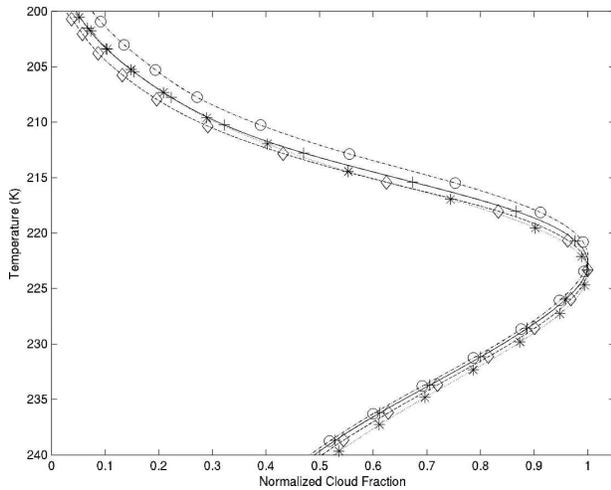
FIG. 4. Normalized cloud fractions as a function of temperature for the control case (solid, +) and cases with doubled CO_2 (dotted, *), doubled stratospheric water (dashed, diamond), and dynamical cooling in the stratosphere (dashed–dotted, circle).

unchanged. However, when the ozone profile is shifted downward by 4 km to 12 km, the detrainment temperature increases as ozone heating starts to exert greater influence on the detrainment level. Such significantly downward-shifted ozone profiles, however, are unlikely in the real atmosphere, especially as tropical deep convection tends to reduce upper-troposphere ozone through the detrainment of ozone-poor boundary layer air. Therefore, for plausible ozone profiles, the decrease in the emission capability of air shall remain the control on the detrainment level, and the FAT hypothesis should hold.

We have also conducted experiments with a doubled CO_2 mixing ratio, doubled stratospheric water vapor concentration, and dynamical cooling due to the Brewer–Dobson circulation, respectively. For the doubled CO_2 run, an SST of 32.5°C was used, and for the other two runs, the SST was 30.5°C. Following previous studies (Thuburn and Craig 2002; Kuang and Bretherton 2004), the upwelling due to the Brewer–Dobson circulation is represented by a dynamical cool-
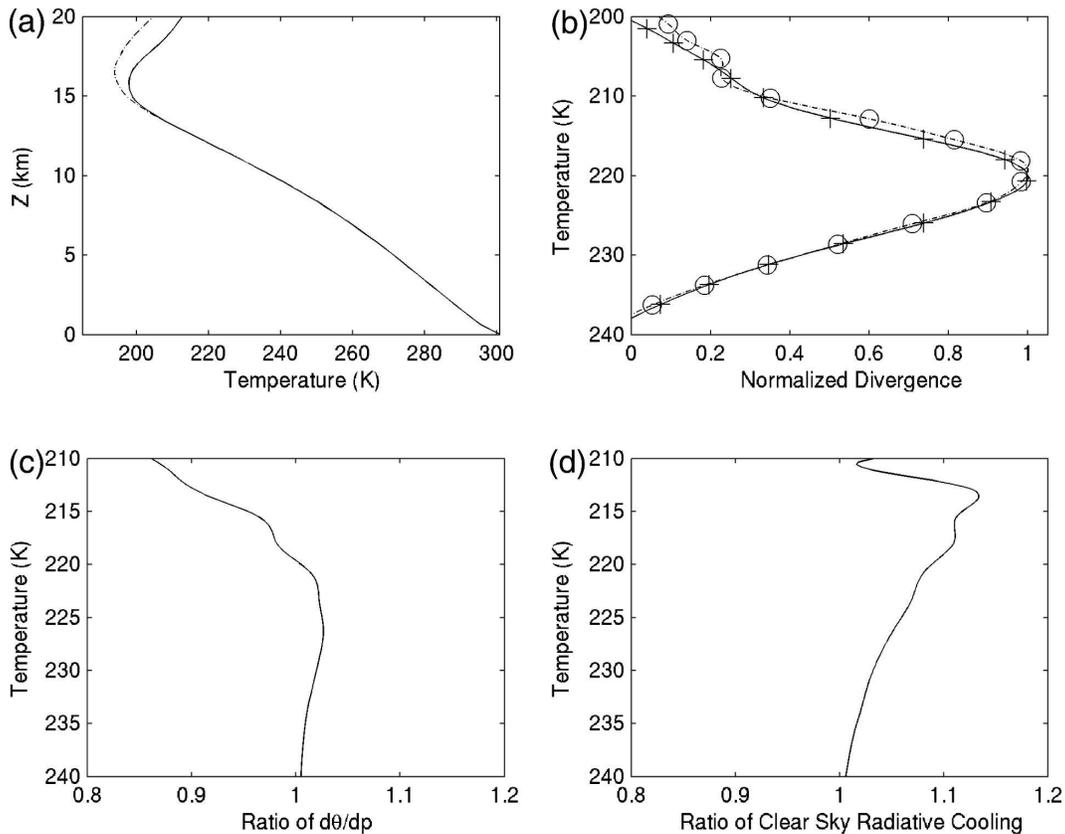

FIG. 5. The (a) temperature profile and (b) normalized divergence as functions of temperature for the control case (solid, +) and the case with dynamical cooling in the stratosphere (dashed–dotted, circle). The ratio of (c) $d\theta/dp$ and (d) clear-sky radiative cooling of the dynamical cooling case to the control case.
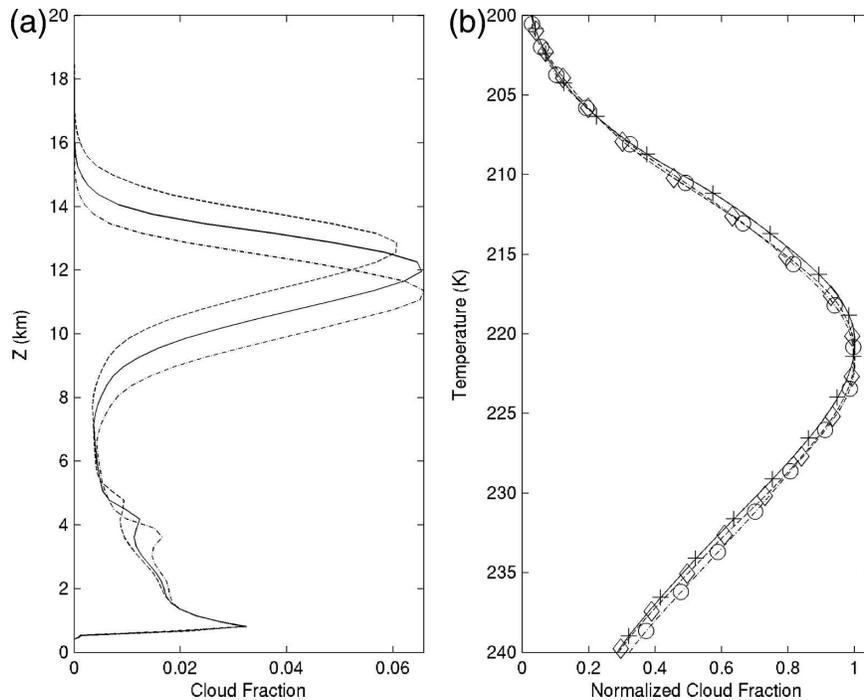
FIG. 6. RCE profiles of cloud fraction as a function of (a) height and (b) temperature for SSTs of 32.5° (dashed, diamond), 30.5° (solid, +), and 28.5°C (dashed–dotted, circle) using the Krueger microphysics.

ing term in the thermodynamic equation. The imposed large-scale vertical velocity is 0.3 mm s^{-1} in the stratosphere and gradually goes to 0 from 100 to 250 hPa, the same as that in Kuang and Bretherton (2004). In all three experiments, the anvil temperature remains approximately unchanged (Fig. 4). The largest change in anvil temperature is seen in the case with dynamical cooling in the stratosphere (~1 K), which is also captured in the divergence field derived from Eq. (2) (Fig. 5b). With the dynamical cooling term, the lower stratosphere is about 8 K cooler compared to the control case (Fig. 5a). The cooler lower stratosphere allows for a greater radiative cooling in the upper troposphere (Fig. 5d). The case with dynamical cooling also has a weaker stratification above about 220 K (Fig. 5c). These two effects cause the 1-K shift in the anvil detrainment level.

We have tested the robustness of our results with respect to the microphysics treatment by repeating the experiments presented in Figs. 1, 2 using a different microphysics scheme (Krueger et al. 1995), which is a modified version of the Lin bulk microphysics scheme (Lin et al. 1983). This scheme was implemented in SAM by P. N. Blossey (Blossey et al. 2007). The results are shown in Fig. 6. With this scheme, the clouds exhibit a clear trimodal distribution with a pronounced peak associated with the melting level, a feature observed in

nature (Johnson et al. 1999). This peak is not as pronounced in simulations with the default SAM microphysics. The cloud covers are also different from the results in Fig. 1. The anvil temperature, however, stays the same with SST changes, indicating that our conclusion on FAT is robust with respect to microphysics schemes used in the model.

4. Conclusions

The fixed anvil temperature (FAT) hypothesis (Hartmann and Larson 2002) was tested using 3D CRM simulations of tropical radiative–convective equilibrium. While an earlier 3D CRM study suggested an increase in the anvil temperature with an increase in SST (Tompkins and Craig 1999), their resolution in the upper troposphere is too coarse (~1 km) for the purpose of testing the FAT hypothesis. Our study uses finer resolution (300 m) in the upper troposphere and a longer integration time to allow sufficient signal-to-noise ratio. Our results strongly support the FAT hypothesis: the anvil temperature changes by less than 0.5 K with a 2-K change in SST. Further experiments suggest that for plausible ozone profiles, a decrease in the air's emission capability instead of ozone heating controls the detrainment level, and the FAT hypothesis should hold. The anvil temperature also remains ap-

proximately unchanged with other changes in the system such as doubled CO_2 mixing ratio, doubled stratospheric water vapor concentration, and dynamical cooling due to the Brewer–Dobson circulations. While the cloud distribution itself is sensitive to the microphysics scheme, the conclusion that the anvil temperature remains approximately unchanged with SST changes is robust when a different microphysics scheme is used. These results therefore support the basic idea behind the FAT hypothesis in the simple setting of RCE over a relatively small domain. How mesoscale and large-scale dynamics would affect the FAT hypothesis is an interesting question that warrants further studies.

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