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THE EFFECTS OF AGGREGATED CONVECTION IN CLOUD-RESOLVED RADIATIVE-CONVECTIVE EQUILIBRIUM

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1. Introduction

Clustering or aggregation of convection is common in the tropical atmosphere. Common examples are squall lines, mesoscale convective complexes, tropical cyclones, and the Madden-Julian Oscillation (MJO). The mechanisms for aggregation can be different for different types of cloud systems, with some mechanisms better understood than the others, but there is generally poor understanding of the possible effects of warming climate on aggregation.

Radiative-convective equilibrium (RCE) has been extensively used in the past as an idealization of the tropical atmosphere. Typically, the sea surface temperature (SST) is prescribed with increasing values emulating the warming climate. It has been demonstrated in cloud-resolving RCE simulations that tropical convection can be in either of at least two stable states: random disaggregated convection and aggregated convection (Bretherton and Khairoutdinov 2004; Bretherton et al 2007). It has been shown that the transition between the aggregated and disaggregated states can depend strongly on SST (Khairoutdinov and Emanuel 2010; Wing and Emanuel 2012). One of the main features of self-aggregation is the close link between convection, radiation, and surface enthalpy fluxes (Bretherton at al 2007; Muller and Held 2012; Wing and Emanuel 2012). It has been shown that removing radiative or surface flux feedbacks generally prevents self-aggregation. One of the intriguing features of self-aggregation is a hysteresis that manifests as a strong tendency for the convection to lock into the aggregated state (Khairoutdinov and Emanuel 2010; Muller and Held 2012). There has also been a realization that self-aggregation can be sensitive to the domain size (Bretherton et al 2007) and grid spacing, with the courser grid conducive to aggregation (Muller and Held 2012).

It has been demonstrated that given sufficient Coriolis force, the aggregated clump of convection develops into a tropical cyclone (Bretherton et al 2007; Nolan et al. 2007). In these earlier studies, the domain size was just large enough for one tropical cyclone (TC). It was not clear if the domain size could influence the results. In this study, we explore self-aggregation with constant Coriolis parameter, the so-called *f*-plane approximation. By artificially increasing the Coriolis parameter well above its values in the real Tropics, we have been able to study the sensitivity of *f*-plane RCE to SST with multiple cyclones coexisting in the same domain, a configuration we nickname ‘TC World’.

2. *f*-plane RCE

a) Model and general set-up

All the RCE simulations presented here have been performed using a full-physics cloud-resolving model (CRM), the System for Atmospheric Modeling (SAM; Khairoutdinov and Randall, 2003). SAM is a three-dimensional non-hydrostatic model with momentum equations in anelastic approximation. We use one-moment bulk cloud microphysics and the interactive radiation package from NCAR’s Community Atmosphere Model version 3 (CAM3). Radiation is computed assuming perpetual sunlight (no diurnal cycle). The SST is specified, but the surface fluxes are interactive. The horizontal domain is doubly periodic with 3-km grid spacing. The vertical grid has 64 levels with the top at 28 km and variable grid spacing. The initial sounding for each SST is specified as the average from the last 10 days of 50-day long runs using a smaller 96x96 km^2 horizontal domain in which convection does not aggregate. The motion is initialized by random temperature noise near the surface. The time step is 20 s.

b) TC World scaling

For rotating fluids, the relative importance of the Coriolis force is generally described by a Rossby number which we here define

$$Ro = \frac{V_{PI}}{f\,D} \qquad (1)$$

where V_{PI} is a characteristic TC velocity scale equal to the Potential Intensity (PI; Emanuel 1995), f is the Coriolis parameter, and D is some characteristic size or diameter of a cyclone. For Ro of the order of one, we get the following estimate for D:

$$D \approx \frac{V_{PI}}{f} \qquad (2)$$

To test if the modeled cyclones scale in accordance with (2), we have conducted two RCE simulations over a large 3000 km domain and two values of the Coriolis parameter, f=5x10^{-5} s^{-1}, and 2x10^{-4} s^{-1}. Note that the former value corresponds to Earth's 20° latitude, and the latter represents a 4-fold increase over that value. Both simulations start from a horizontally uniform initial state with random temperature noise near the surface, and prescribed SST=300K. Similar to the numerical experiments of Nolan et al (2007), the tropical cyclones develop in about two-three weeks of simulation time as illustrated by Fig. 1. One can see that in these *f*-plane RCE runs, the scaling (2) seems to work fairly well in predicting the characteristic size of the cyclones.

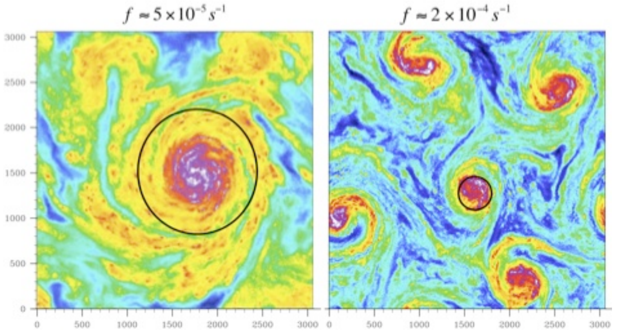

Figure 1 Simulated tropical cyclones for two different values of Coriolis parameter in otherwise identical RCE simulations. The superimposed circles show the characteristic sizes of the cyclones as estimated from the expression (2).

c) Dependence on TC size and intensity on SST

In order to minimize the effect of the domain size on the statistics of simulated tropical cyclones, the domain size should be chosen big enough to contain multiple tropical cyclones. For typical values of the Coriolis parameter in the Tropics where hurricanes are common (10-20° latitude), the domain size would have to be 2-3 times larger than the domain shown in Figure 1 (3000 km). We use (2) to reduce computational requirements for *f*-plane RCE runs, which can be as long as a few hundred days. In this preliminary study, the available computational resources have constrained the domain size to 1152 x 1152 km^2 in runs with Coriolis parameter f=5x10^{-4} s^{-1}. The runs were 100-150 days long. The SSTs were fixed in rather wide range: 294, 297 and 300K. To see the effect of rotation on RCE statistics, the complimentary no-rotation runs have also been conducted with a smaller horizontal domain size of 384 x 384 km^2, primarily to avoid self-aggregation into a clump. In each run, the mean statistics were obtained by averaging daily statistics over the last 50 simulation days.

Snapshots of near-surface wind velocity after about two months of simulation time for each of the values of SST are shown in Figure 2. One can see that the size of cyclones tends to monotonically increase with the SST and so does their intensity (Figure 3). It also appears that the radius of maximum wind tends to increase with SST.

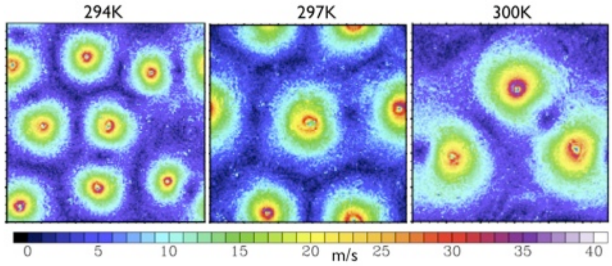

Figure 2 Snapshots of near-surface wind (in m/s) in RCE with rotation for three different values of the SST.

The scaling given by (2) implies that the spatial frequency (number per unit area) of tropical cyclones in TC World varies as $f^2 V_{PI}^{-2}$, while the power dissipation per unit area should scale as V_{PI}^3. Thus tropical cyclones become less frequent but more intense as temperature increases in TC World.

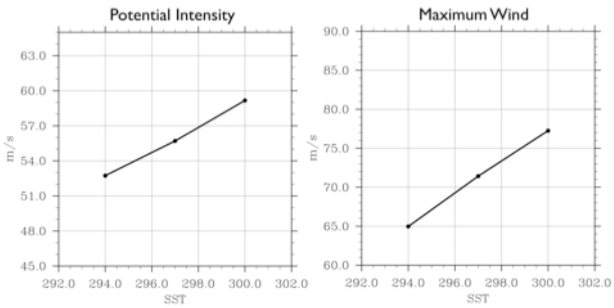

Figure 3 Emanuel's Potential Intensity (left panel) and daily instantaneous maximum wind anywhere in the model grid as a function of SST in TC-World.

d) The effect of SST change on tropopause and outflow temperature

The effect of the SST on simulated tropopause in RCE with and without tropical cyclones is demonstrated in Fig.4*a*. The most apparent effect of rotation is that the simulated troposphere in the 'TC World' seems to be considerably deeper, by about 2 km, then the troposphere with no rotation. Also, it is apparent that the air in the upper troposphere tends to warm more than the near-surface air. This is well explained by the smaller vertical temperature gradient, which in Tropics is close to moist adiabatic, which becomes smaller with increasing temperature.

One might expect that the TC outflow temperature tracks the upper troposphere temperature, i.e., it would increase with increasing SST. The simulation results suggest otherwise (see Figure 4). We define the outflow temperature as the temperature of the level where the cloud fraction is maximum. To clearly see that level, we plotted the cloud fraction as the function of temperature rather than height. The result is shown in Figure 4*b*. One can see that simulated outflow temperature is invariant with SST. (A similar plot for the no-rotation runs shows similar behavior.) Thus, the simulations seem to support the so-called Fixed Anvil

Temperature hypothesis (FAT; Hartmann and Larson 2002). The FAT hypothesis has been tested in cloud-resolving RCE simulations by Kuang and Hartmann (2007). Our results extend the test of the hypothesis to the case of tropical cyclones. The invariance of the outflow temperature implies increasing thermodynamic efficiency of simulated tropical cyclones with increasing SST.

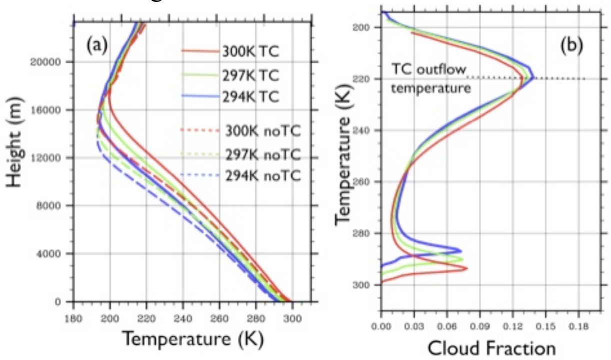

Figure 4 Vertical profiles of (a) temperature and (b) cloud fraction for different SSTs in RCE with (solid lines) and without rotation (dashed lines). Note that in b) the temperature rather than height is used as the vertical coordinate.

e) Climate sensitivity of f–plane RCE

The RCE simulations presented in this study have been performed over fixed SSTs. As a result, the simulations are not required to have zero top-of-atmosphere (TOA) and surface energy balance. In nature, this imbalance is compensated by transport of energy away from or into the column by the atmosphere and the ocean. The magnitude of imbalance depends on the SST, and we can use this dependency to estimate the climate sensitivity of our RCE simulations.

The energy balance of the modeled atmosphere system would require that

$$N - Q + F \approx 0 \qquad (3)$$

where N is the TOA radiative flux imbalance, Q the implied divergence of ocean transport, and F the external forcing. Such an external forcing could be, for example, due to increased concentrations of the greenhouse gases. Both Q and F would be needed to keep the SST at a prescribed value if we had an interactive ocean model. Differentiating (3) with respect to SST denoted by T_s, we can express the equilibrium climate sensitivity parameter

$$\lambda_c \equiv \frac{dF}{dT_s} \qquad (4)$$

as the following:

$$\lambda_c = -\frac{dN}{dT_s} + \frac{dQ}{dT_s} \qquad (5)$$

Thus, the climate sensitivity of our idealized tropical atmosphere can be computed from the change of the net TOA flux and implied transport given the change of SST. The last term in the right-hand-size of (4) cannot be determined from the RCE simulations. (Note that when integrated globally, this term drops out). The first term in (4) is given by the slope of the *N-SST* graph as shown in Fig. 5.

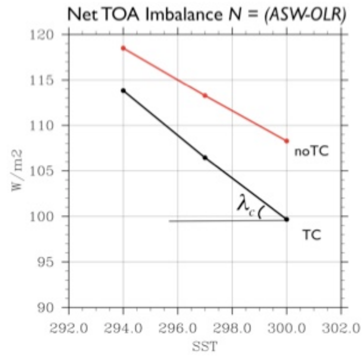

Figure 5 Net top-of-atmosphere (absorbed solar minus outgoing longwave) radiation flux as the function of the prescribed SST in *f*-plane RCE simulations with tropical cyclone (black line) vs simulations with no tropical cyclones (red line). The negative slop of each line equals to the equilibrium climate sensitivity parameter defined by (4).

From Figure 5 we infer that the presence of tropical cyclones tends to increase λ_c (by about 40% if we assume that there is no change in Q) and, hence, tends to decrease the climate sensitivity of the RCE. Our preliminary analysis indicates that it is the change in the absorbed solar radiation that is mainly responsible the difference in slopes in Figure 5. To the degree that RCE can be viewed as a suitable idealization of Tropics, we can hypothesize that the presence of tropical cyclones may mitigate the effect of anthropogenic increase of greenhouse gases on tropical SSTs. Note that the global climate models do not generally have this negative feedback as they do not have enough resolution to adequately represent tropical cyclones in climate-change simulations. Therefore, the climate sensitivity, particular of Tropics, may be overestimated by the GCMs.

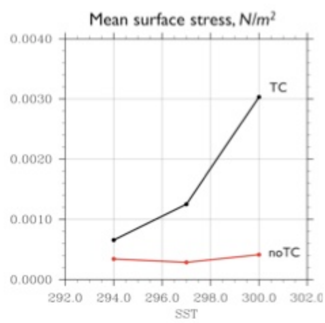

Figure 6 Mean surface stress as a function of the prescribed SST in *f*-plane RCE simulations with tropical cyclones (black line) vs simulations with no tropical cyclones (red line).

Concerning the sensitivity of the implied heat transport to SST, we note that in the deep Tropics much of the poleward transport is due to the ocean (e.g., Trenberth and Fasullo, 2008). As was hypothesized by Emanuel (2001), the additional mixing in the upper ocean due to tropical cyclones could increase the poleward ocean transport of heat. In our RCE, the surface stress increases considerably with SST as illustrated by Fig. 6. Such stress increase could increase the ocean mixing, and, hence, Q. According to (5), the increased Q would further increase λ_c and, hence, further reduce the climate sensitivity. Thus, both effects of tropical cyclones -- on TOA radiation and on ocean transport -- could potentially have a negative feedback on climate change in the deep Tropics.

3. Summary

We have demonstrated that the characteristic size of tropical cyclones follows a simple dimensional scaling based on the potential intensity (PI) velocity and the Coriolis parameter. We have conducted *f*-plane RCE simulations with cranked up Coriolis parameter, which allowed us to reduce the horizontal domain size required to simultaneously contain several tropical cyclones to minimize the effect of the domain size on the results. The RCE simulations, with and without rotation, have been conducted for three different values of the SST: 294, 297, and 300K. The RCE with different SSTs can be viewed as a proxy for studying climate change in Tropics. The main findings of this study are:

- The size and intensity of simulated tropical cyclones monotonically increase with SST;
- The tropopause in RCE with rotation can be substantially higher (by about 2 km) than in RCE with no rotation;
- The outflow temperature defined as the temperature of maximum cloud fraction stays constant despite the SST increase in both TC-World and nonrotating RCE;
- The equilibrium climate sensitivity in TC-World is lower than in nonrotating RCE.

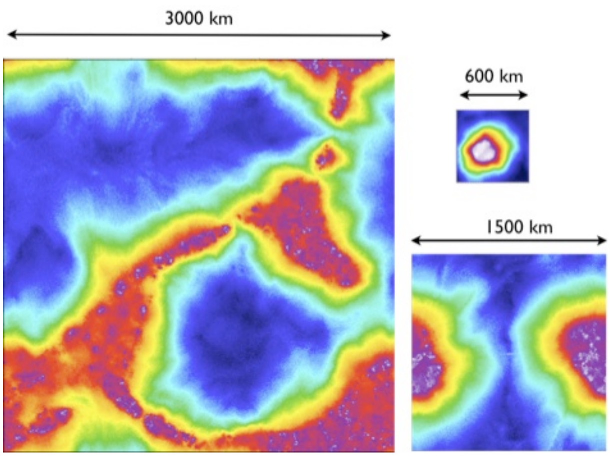

Figure 7. Precipitable water at the end of RCE simulations with different horizontal domain sizes.

4. Is the MJO a self-aggregated clump?

Self-aggregation in idealized RCE simulations with no rotation does not seem to have a horizontal limiting scale. In the previous numerical studies of RCE with no rotation, the horizontal domain size has not generally exceeded 600 km (Bretherton et al. 2005, Khairoutdinov and Emanuel 2010, Muller and Held 2012, Wing and Emanuel 2012). The question is whether there is a horizontal limiting scale for self-aggregation in such a nonrotating framework. To try to answer this question, we have conducted several self-aggregation experiments in domains as large as 1500 km and 3000 km, as shown in Figure 7. One can see that the aggregated clump in the 1500-km domain looks quite similar to the clump in the 600-km domain. Due to high computational expense, the 3000 km has not been run to the formation of a round convective clump; however, the evolution of that run allows us to speculate that given enough time the round clump would eventually form. These runs do suggest that self-aggregation in RCE does not have a horizontal limiting scale.

However, there is an ultimate limiting horizontal scale for any phenomenon on Earth: the circumference of the Earth itself. There is one particular phenomenon in the deep Tropics that tends to grow to that ultimate planetary scale – the MJO. In the deep Tropics, the magnitude of the planetary vorticity is small, which can be approximated by nonrotating RCE in the zonal direction. Is the MJO simply a self-aggregated clump of convection on the equatorial beta-plane? To test this hypothesis we are currently performing cloud-resolving idealized beta-plane RCE simulations over a large (16384x8192 km^2) domain for tens of days. A snapshot of the cloud field from one of such simulations is shown in Figure 8.

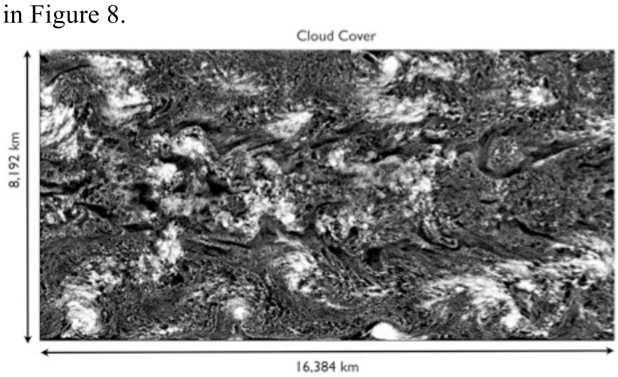

Figure 8 A snap-shot of a simulated cloud cover in the idealized beta-plane RCE simulation over prescribed constant SST. The equator is in the middle of the domain.

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