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AGGREGATED CONVECTION AND THE REGULATION OF TROPICAL CLIMATE

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1. INTRODUCTION

Moist convection in the Earth's atmosphere is mostly composed of relatively small convective clouds that are typically a few kilometers in horizontal dimension (Byers and Braham, 1948, Malkus, 1954). These often merge into bigger clusters of ~10 km in horizontal dimension, such as air-mass showers. More rarely, under special circumstances, moist convection is organized on even larger scales; this includes squall lines (e.g. Houze, 1977), mesoscale convective complexes, (e.g. Maddox, 1980), and tropical cyclones.

Convection is a response of the atmosphere to destabilization by column processes such as surface enthalpy fluxes and radiative cooling, and also by large-scale circulation of atmosphere and associated enthalpy transport. On long space and time scales, convection is often viewed as being in quasi-equilibrium with the forcing, that is, convective clouds stabilize the atmosphere at exactly the rate it is destabilized by large-scale processes (Arakawa and Schubert, 1974, Emanuel et al., 1994). In the simplest form of such equilibrium, the so-called radiative-convective equilibrium (RCE), the effects of large-scale circulation on convection are ignored, and only radiation, convection, and surface enthalpy fluxes are allowed to transfer energy. It is understood that the RCE is an idealization of nature; however, despite its comparative simplicity, it is a reasonable framework for understanding convective equilibrium states.

The RCE states were first simulated using one-dimensional models with parameterized convection (e.g. Rennó et al., 1994), and, consequently, the states that require spatial clusters of clouds have not been modeled. In the last two decades, advances in computer power have made it possible to use cloud-system-resolving models (CRMs) to simulate RCE in domains large enough to contain many convective clouds (e. g. Held et al., 1993, Islam et al., 1993, Robe and Emanuel, 1996, Bretherton and Khairoutdinov, 2004, Bretherton et al., 2005, Nolan et al., 2007). When relatively small three-dimensional domains with sizes in the order of a hundred kilometers are used, the simulated convective cloud fields appear nearly random in space and in time (Islam et al., 1993). When much bigger domains are employed and certain conditions are met, the convection tends to self-aggregate into a single clump (Bretherton and Khairoutdinov, 2004; Bretherton et al., 2005), which, if subjected to sufficient Coriolis force, can develop into a tropical cyclone (Nolan et al., 2007).

Several conditions have been identified that seem to be necessary for self-aggregation to occur (Held et al. 1993; Bretherton et al., 2005; Nolan et al. 2007). Among them are small vertical shear of the horizontal wind, interaction of radiation with clouds and/or water vapor, and effect of convectively enhanced surface winds on surface fluxes. Although Nolan et al. (2007) demonstrated that reducing the SST could increase the time to spontaneous tropical cyclogenesis in RCE, there has been basically no systematic study of the dependence of self-aggregation on the sea-surface temperature (SST). In this extended abstract, we report on the results of the first such study, using both a simplified model and a CRM to simulate self-aggregation with different SST. A strong nonlinear dependence of self-aggregation on SST leads us to hypothesize that tropical convection can be in the state of a self-organized criticality (SOC; e.g. Bak et al., 1987), which is analogous to the critical point in phase transition. There have already been studies suggesting that observed tropical convection may indeed exhibit SOC-like behavior (Peters and Neelin, 2006; Muller et al., 2009). Here, we formulate an SOC hypothesis for tropical convection and present results supporting the SOC hypothesis in an idealized RCE setting.

2. SOC HYPOTHESIS

One of the robust characteristics of self-aggregation is the rather dramatic change in the mean state that accompanies it. In particular, in all non-rotating experiments (Bretherton et al., 2005) and an experiment on an f-plane (Nolan et al., 2007), self-aggregation leads to dramatic drying of the domain-averaged environment above the boundary layer. This appears to be the result of more efficient precipitation within the convective clump as more of the condensed water falls out as rain and less is detrained to the environment, per unit updraft mass flux. Such dramatic drying would reduce the greenhouse effect associated with the water vapor, and thus, would lead to cooling of the SST, which in turn

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**Corresponding author's address*: School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY 11794-5000; email: *Marat.Khairoutdinov@stonybrook.edu* may disaggregate convection. This would re-moisten the atmosphere, increasing the water-vapor greenhouse effect, and, consequently, warming the system. So, as in SOC, the tropical state would be attracted to the transition critical state between the aggregated and disaggregated states.

3. RESULTS

a) Simplified Toy Model

To determine whether RCE with the energy balanced surface can indeed achieve SOC, we conducted preliminary experiments with a 'toy' model in which the radiative transfer occurs only in a limited number of layers, convection is parameterized using the subcloud-layer quasi-equilibrium closure (Raymond, 1995), and simple parameterizations account for the convective gustiness effects on surface fluxes. A general structure of the simplified model is illustrated in Fig. 1.

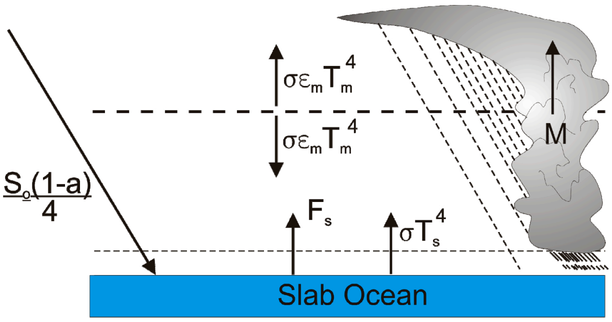

Figure 1. Characteristics of the simplified model. In its most primitive form, the atmosphere consists of a single layer of temperature T radiating with an emissivity ε_m which is a function of the humidity of the atmosphere. The surface, at temperature T_s, radiates with unit emissivity. The incoming solar radiation at the top of the atmosphere is S_o, and the albedo a, which may depend on cloud fraction. There are surface turbulent enthalpy fluxes given by F_s, and the cumulus mass flux M is determined from subcloud layer quasi-equilibrium.

Despite its simplicity, the model has the feedback between atmospheric humidity, which depends on the fractional coverage of convective clouds, and the longwave emissivity, which is a key feedback for achieving the self-aggregation. At low fixed SST, the model exhibits uniform convection with no self-aggregation. At high fixed SST, the convection aggregates into a single meso-scale cluster driven by convective gustiness feedback. The aggregated state is characterized by a profoundly dryer troposphere. When SST is interactive, the model does behave in accordance with the SOC hypothesis, reaching a state of SOC and remaining near the critical temperature (Fig. 2). Interestingly, the climate sensitivity of the SOC state is much lower (0.04 K/Wm-2) than the sensitivity of the uniform convection state (0.2 K/Wm-2). We note that the current generation of climate models has no way of simulating this kind of SOC state.

b) Cloud-System-Resolving Model

We have also conducted several preliminary RCE simulations using a full-physics CRM, which is the System for Atmospheric Modeling (SAM; Khairoutdinov and Randall, 2003). SAM is a three-dimensional non-hydrostatic anelastic model with bulk cloud microphysics and interactive radiative-transfer scheme. The previous self-aggregation studies by Bretherton and Khairoutdinov (2004) and Bretherton et al. (2005) used earlier versions of the same model. The first objective was to establish whether self-aggregation is indeed temperature dependent. To that end, we conducted the RCE simulations over fixed SSTs in the range from 293 K to 305 K. The simulations' set-up closely followed Bretherton et al. (2005). The horizontal doubly periodic domain size was 576 x 576 km2 with a grid spacing of 3 km. The vertical grid had 64 levels with the top at 27 km and variable grid spacing. For each SST, the model was spun-up for 50 days using a smaller 96 x 96 km2 horizontal domain that was too small for self-aggregation. The thermodynamic profiles averaged over the last 10 days of the small-domain runs were used as initial profiles for the large-domain 100-day long runs.

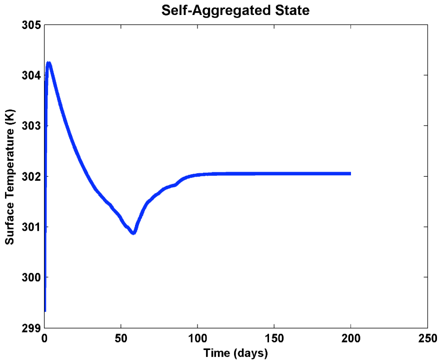

Figure 2 Evolution with time of the surface temperature using the simple model summarized in Fig.1.

The results for different values of the surface temperature are shown in Fig. 3. Clearly, there is an abrupt transition between two RCE regimes when the SST is near 297 K. Below the threshold temperature, convection does not aggregate at all, at least for 100 days. Above the threshold, convection always self-aggregates leading to significant drying of the troposphere above the boundary layer and, as a result, to significant increase in the outgoing longwave flux, which is an indication of a reduced greenhouse effect.

In the second set of experiments, a simple slab-ocean model was used to compute the SST from the net flux at the ocean surface. The slab is chosen to be rather thin, just 2 m, so that the statistical equilibrium can be achieved in a reasonable time. To compensate for the undesirable inhomogeneity of the SST due to thinness of the ocean slab, shading by the anvils, gustiness, and other local effects, the SST was horizontally homogenized at each time step. The preliminary runs revealed very strong hysteresis of the modeled system. As expected, after aggregation, the SST starts falling; however, to our surprise, the convection does not disaggregate even when the SST falls well below the critical threshold temperature established by the earlier fixed-SST runs. The convection seems to be locked in the aggregated state, presumably because the subsiding free troposphere surrounding the convective clump is too dry to support deep or even mid-level convection. Further analysis of this system is needed to come up with the strategies to overcome this difficulty.

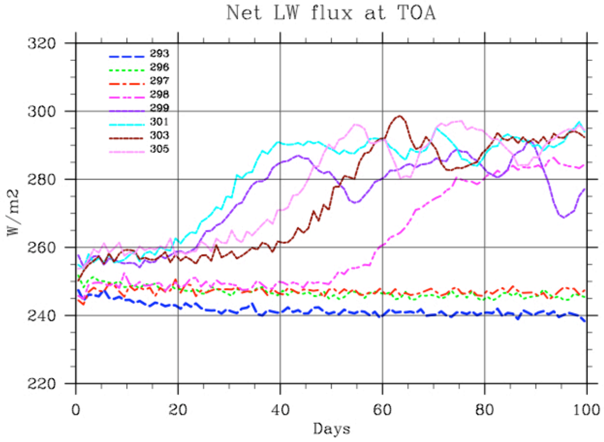

Figure 3 Net outgoing longwave flux averaged over top of the model domain, as a function of time, for eight values of the surface temperature using the CRM.

4. SUMMARY

Idealized simulations of radiative-convective equilibrium suggest that the tropical atmosphere may have at least two stable equilibrium states or phases, one is convection that is random in time and space, and the second is the spontaneously aggregated convection. In this study, we have demonstrated using a simplified and full-physics cloud-system-resolving models that there is an abrupt phase transition between these two equilibrium states depending on the surface temperature, with higher SST being conducive to the aggregation. A significant drying of the free troposphere and consequent reduction of the greenhouse effect accompany self-aggregation; thus, the sea-surface temperature in the aggregated state tends to fall until convection is forced to disaggregate. This leads to the hypothesis that when surface temperature is allowed to adjust to variations of net surface fluxes, the convection may be attracted toward a self-organized critical state between aggregated and disaggregated states. Tests using a simplified toy model seem to support this hypothesis. The toy model also demonstrates that the climate sensitivity of this self-organized critical state is much lower than the sensitivity of the conventional radiative-convective equilibrium. Preliminary results using a full-physics cloud-system-resolving model reveal strong hysteresis of the modeled system, which manifests itself as a tendency for convection to lock into the aggregated state. More research is needed to better understand this behavior.

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