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THE SENSITIVITY OF MULTIPLE EQUILIBRIA TO SEA SURFACE TEMPERATURE CHANGES IN WEAK TEMPERATURE GRADIENT SIMULATIONS

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1. INTRODUCTION

The response of the tropical atmosphere to global temperature changes is important for understanding the development of phenomena originating in the tropics, e.g. hurricanes and the Maden-Julian oscillation. Observations show that areas of developing synoptic systems exhibit self-aggregation of convection, the process of drying out of the atmosphere in favor of a sharply defined moist region. The study of self-aggregation can lead to increased knowledge of tropical cyclogenesis and other phenomena originating in the tropics. Model simulations by Khairoutdinov and Emanuel (2010) found that self-aggregation in a cloud resolving model (CRM) with radiative convective equilibrium (RCE) boundary conditions exhibits a strong nonlinear dependence on SST.

Investigating self-aggregation in large RCE domains is computationally expensive. Multiple equilibria in smaller domains which utilize the weak temperature gradient (WTG) approximation (Sobel et al. 2007, Sessions et al. 2010) may provide an alternate strategy to understand conditions which promote self-aggregation on larger domains. In this case multiple equilibria refers to either a precipitating or non-precipitating state, depending on initial moisture content of the model domain. In Sessions et al., multiple equilibria occurred only for wind speeds smaller than a critical value.

In this paper we show that the critical wind velocity which separates the multiple equilibrium region from a single, precipitating regime is a strongly nonlinear function of SST. Linked with findings of Khairoutdinov and Emanuel, this implies a possible connection of multiple equilibria in a limited domain CRM to self-aggregation of convection in RCE simulations.

In section 2 we explore the WTG approximation, In section 3 we discuss our current results. Section 4 gives the conclusions and ongoing work.

2. WEAK TEMPERATURE GRADIENT APPROXIMATION

Effectively, the WTG approximation parameterizes the large scale in a limited domain CRM. It assumes weak horizontal gradients of equivalent potential temperature in the tropical environment. Any perturbations arising in the vertical profiles of temperature due to convection are radiated out by gravity waves. In a CRM, this can be achieved by imposing a hypothetical vertical velocity that counteracts radiative heating. In our CRM the perturbed profiles are relaxed to a reference profile at the rate t_θ, physically interpreted as the time that it takes for a gravity wave to cross the domain.

The simulations presented here use the CRM of Raymond and Zeng (2005) with a two dimensional 100 km domain and WTG relaxation time t_θ of 0.51 hours. Reference profiles were calculated by averaging over the last 60 days of RCE simulations with different imposed SSTs. These profiles were then used for WTG simulations with two control variables: initial troposphere moisture, and horizontal wind speed.

3. EXPERIMENTS AND RESULTS

In order to test the sensitivity of multiple equilibria to changes in SST, we first generated reference profiles with RCE simulations for SSTs ranging from 294 K to 305 K. Each of these represented different large scale conditions, and all WTG simulations prescribed SSTs equivalent to the respective RCE reference profile. For each SST, parallel WTG experiments were performed in which the initial atmospheric moisture was either completely dry or equal to the moisture profile of the ambient environment. The experiments also varied wind speed to determine a range of values which support both equilibrium states.
Figure 1 shows the dependence of the precipitation rate on horizontal wind speeds ranging from 3 to 20 m/s and SSTs from 300 to 305K (line color), for moist (solid line) and dry (dashed line) initialized simulations. Note that there is a range of wind speeds that sustain two equilibrium states, a precipitating and a non-precipitating state. Also, note that the critical horizontal wind speed that separates multiple equilibria from the single equilibrium is a non-monotonic and nonlinear function of SSTs. Further, a monotonic increase in precipitation with horizontal wind speed is noticeable.

The dependence of multiple equilibria to changes in SST and horizontal wind speed is shown in Figure 2. All plotted points represent dry initialized simulations. Red shading increases with temperature. The filled boxes represent runs that exhibited a precipitating steady state while empty boxes represent non-precipitating steady state runs. The critical wind speed is identified as the wind speed at which precipitation occurs with dry initial conditions,

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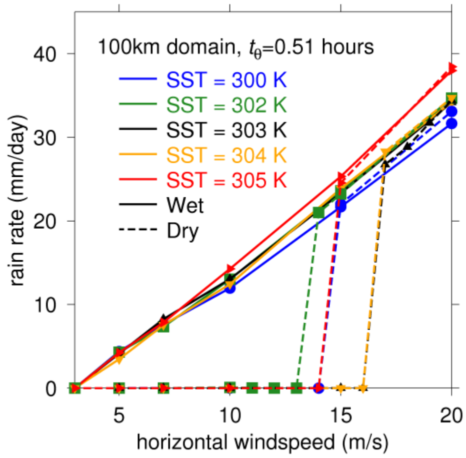

Figure 1**:** Precipitation as a function of horizontal wind speed and different SSTs. Solid lines were initialized with a moist troposphere, dashed lines were initialized dry. The critical velocity marks where the non-precipitating equilibrium is destroyed and a single precipitating equilibrium exists.

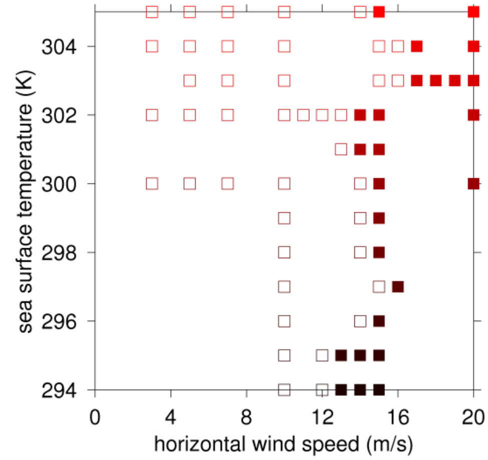

Figure 2: Dependence of multiple equilibria on SST and horizontal wind speed. All points were initially dry simulations. Filled (empty) squares represent precipitating (non-precipitating) equilibrium. Note the highly nonlinear dependence of the critical velocity on SST. Shading indicates increasing SST.

indicating the transition from multiple to a single equilibrium. Figure 2 shows the dependence of the critical wind speed on SST is nonlinear down to 294 K. Preliminary results show that this behavior is not sensitive to initial perturbations in the model. One might expect that with lower (higher) SSTs, higher (lower) wind speeds would be necessary to produce surface moisture fluxes large enough to initiate precipitation. This would imply that smaller (larger) SSTs would support a larger (smaller) range of wind speeds at which the dry equilibrium occurs. However, for SSTs of 294 K and 295 K, we find a smaller range of horizontal wind speeds sustaining the dry equilibrium (multiple equilibria exist only for wind speeds of 12 m/s or less). Also, SSTs of 303 K and 304 K exhibit a larger range of horizontal wind speeds sustaining the dry equilibrium (multiple equilibria exist for wind speeds up to 16 m/s). This might point to a negative feedback mechanism between the horizontal wind speed and moisture fluxes. Further work is necessary to confirm this.

To elucidate the nonlinear dependence of multiple equilibria to SST we consider the normalized gross moist stability (NGMS). The NGMS used here is defined as the ratio of lateral moist entropy export to lateral moisture import. It can be viewed as a measure of precipitation efficiency (see Raymond et al., 2009, for a thorough discussion on NGMS). Figure 3 shows NGMS as a function of horizontal wind speed for initially dry domains. High positive values of NGMS for the precipitating equilibrium states are a result of an export of moist entropy and import of moisture. The non-precipitating equilibrium states observe small positive and negative values; in this case, moisture is exported and small amounts of moist entropy are either imported or exported. For the dry equilibrium there is a distinct jump that occurs in the NGMS at 10 m/s horizontal wind speed that extends to higher wind speeds. NGMS at 3, 5, and 7 m/s only decreases with increasing SST, while for higher wind speeds NGMS increases for increasing SST. Though we currently do not understand this behavior, we hypothesize that understanding this can lead to better understanding of mechanisms leading to multiple equilibria, and possibly self-aggregation.

Figure 4 shows the dependence of NGMS on saturation fraction, defined as the column integrated mixing ratio divided by the column integrated saturated mixing ratio. We see a strong monotonic dependence of NGMS to saturation fraction for the precipitating equilibrium states that increases with SST. The figure exposes a striking pattern in the non-precipitating equilibrium states which is consistent with the separation in Figure 3. This suggests that

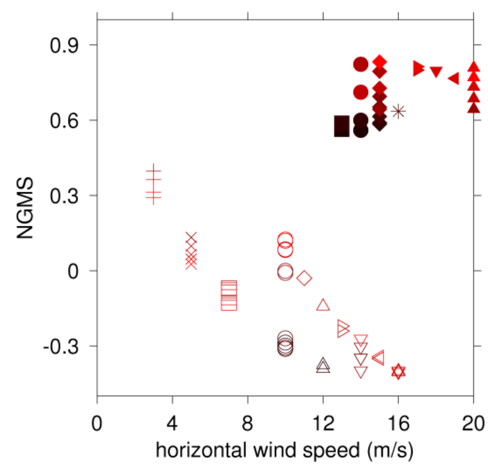

Figure 3: NGMS as a function of horizontal wind speed. Symbols corresponding to wind speed serve as a legend for figure 4. Shading turns to red for higher SST. There is a distinct boundary between precipitating (filled symbols) and non-precipitating (empty symbols) equilibrium states. The non-precipitating states also exhibit a jump obvious at 10 m/s.

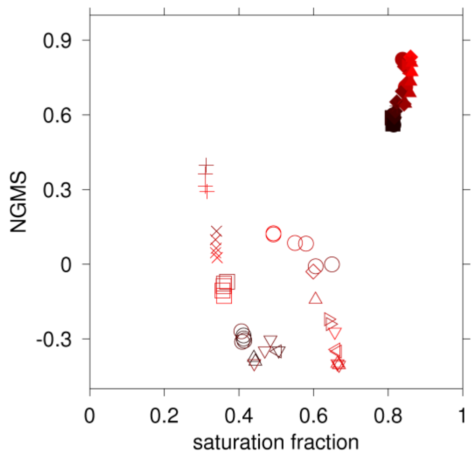

Figure 4: NGMS as a function of saturation fraction. Symbols represent wind speed (see figure 3), precipitating (non-precipitating) steady states are represented with filled (empty) symbols. The non-precipitating steady states exhibit a distinct pattern. The separation visible in figure 3 is even more evident. The precipitating steady states show how NGMS is a strong monotonically increasing function of saturation fraction.

there is a mechanism closely related to moisture and moisture transport which is responsible for the onset of precipitation and the destruction of the dry equilibrium. More work is needed to understand this fully.

4. CONCLUSION AND FUTURE WORK

In this paper we present results of ongoing work investigating multiple equilibria simulations in a limited domain cloud resolving model utilizing the weak temperature gradient approximation. We hypothesize that this will provide insight to self-aggregation in large domain radiative convective equilibrium simulations.

We find that multiple equilibria simulations exhibit strong nonlinear dependence to sea surface temperature which is visible in the critical imposed horizontal wind speed bounding the multiple equilibria from the single equilibrium state (figures 1 and 2). Khairoutdinov and Emanuel (2010) found that the self-aggregation of convection has strong nonlinear dependence to sea surface temperatures. Perhaps the nonlinear dependence of both the self-aggregation and multiple equilibria simulations show a similar physical origin, and understanding this behavior on small weak temperature gradient domains will be a computationally economical way to study self-aggregation.

In future work, we would like to directly compare self-aggregation in radiative convective equilibrium simulations to multiple equilibria in weak temperature gradient simulations. We also intend to understand the behavior of the normalized gross moist stability in this context.

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