Weak temperature gradient approximation in a cloud system resolving model; a tool for studying convection in a changing tropical climate

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PRELUDE

Research shows that climate change could lead to the development of less frequent but more intense hurricanes, which have a noticeable destructive impact. Further, hurricanes are known to transition into extra-tropical cyclones, which can have a considerable effect on the middle latitudes in the form of floods and other extreme weather. Understanding the development of cyclones in their cradle (tropical atmosphere) can lead to better prediction of extreme weather which could save lives and economies.

CONVECTIVE ORGANIZATION

Hurricanes are an example of organized convection in which an intensely precipitating and cloudy region is surrounded with dry cloudless regions (Figure 1). Recent research has shown that convective organization can develop from ostensibly quiescent conditions. Randomly scattered convection aggregates into a well defined precipitating area at the expense of drying out the large scale environment. This process is called self-aggregation (SA) of convection, since it develops in absence of an obvious external mechanism. Also, it has a tendency to happen over warmer sea surface temperatures (SST). That is why it is especially important to study SA in a warming climate (i.e. higher SSTs).

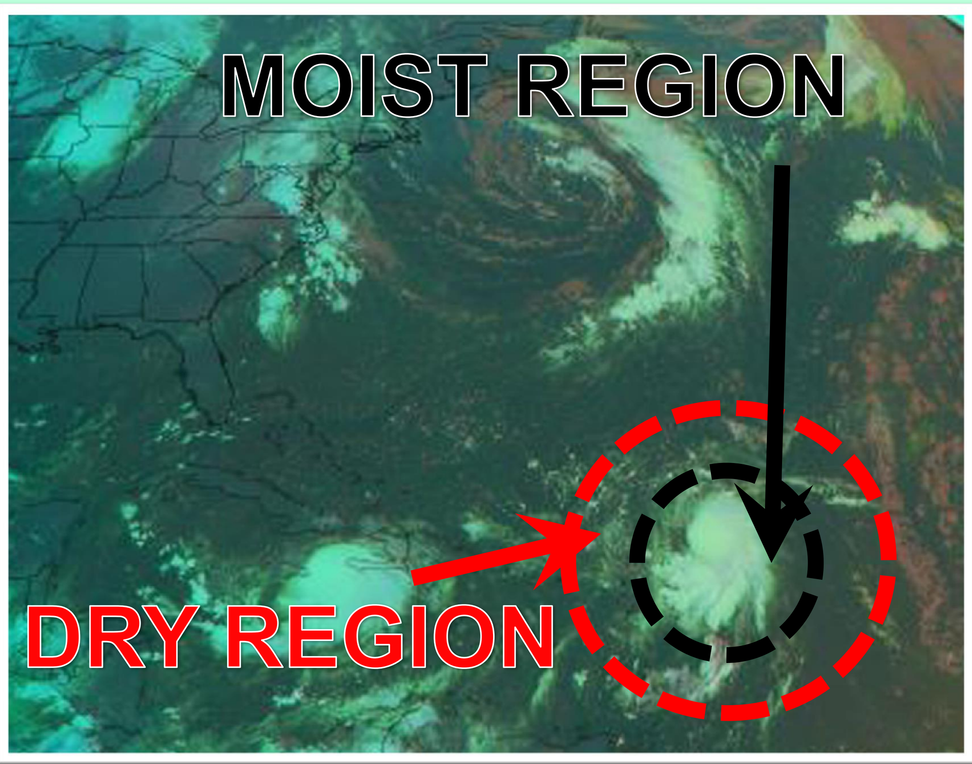

Fig.1. Tropical cyclone as an example of convective organization.

Numerical studies of SA are computationally expensive because they require large domains (~500 km by 500 km) and high resolution (~1 km in the horizontal). Our goal is to develop a method to study SA more efficiently using the weak temperature gradient (WTG) approximation.

WEAK TEMPERATURE GRADIENT APPROXIMATION

The WTG approximation is based on the assumption that gravity waves dissipate potential temperature anomalies in the tropics, and thus maintain weak horizontal gradients of potential temperature. In our model, WTG is enforced by relaxing potential temperature anomalies to a reference temperature profile. This creates a WTG vertical velocity which acts to entrain or detrain moisture from a reference moisture profile by independently satisfying a mass continuity equation. Reference temperature and moisture profiles are obtained by running the model in non-WTG mode until it reaches radiative convective equilibrium (RCE), in which radiative cooling balances the convective forcing. Figure 2 shows RCE profiles for different SSTs, going from lower (295 K; cooler climate) to higher (305 K; warmer climate).

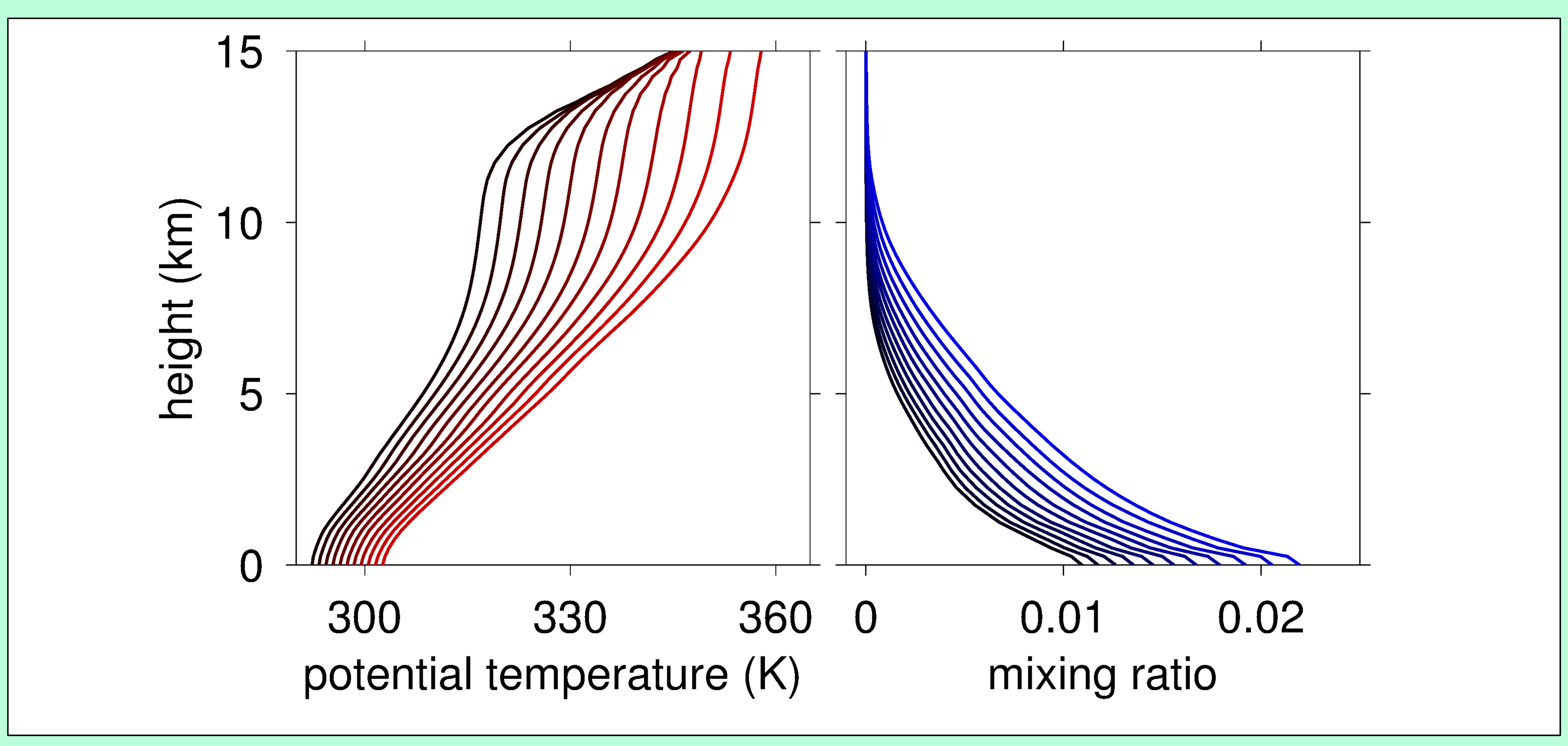

Fig.2. Radiative convective equilibrium profiles of temperature and moisture. These profiles are reference profiles for WTG simulations.

MULTIPLE EQUILIBRIA AND ORGANIZATION

A study by Sessions et al. (2010) investigated multiple equilibria in precipitation in the cloud system resolving model of Raymond and Zeng (2005), a research grade idealized model of the tropical atmosphere. Multiple equilibria are defined as a precipitating or non-precipitating steady state for the same boundary conditions but different initial conditions. The initial condition is a dry or moist moisture profile, and the boundary conditions are imposed wind speed, SSTs, and reference temperature and moisture profiles. Figure 3 (left), shows an example of multiple equilibria for a SST of 303 K. Rain rate is plotted against horizontal wind speed, and multiple equilibria, a dry and precipitating state, extends from 3 m/s to 14 m/s. There is a single precipitating equilibrium for wind speeds higher than the critical wind speed of 14 m/s. In Figure 3 (right) we can see "the top view" of figure 3 (left), where squares represent dry initialized simulations. Filled symbols represent runs that eventually precipitated, while empty symbols present non-precipitating runs. The black solid curves correspond to the critical wind speed from figure 3 (left). We can notice a highly nonlinear behavior in the critical wind speed as a function of SST. The multiple equilibria are constrained to a narrower range of wind speeds for higher SSTs (warmer climate) than for lower SSTs (cooler climate).

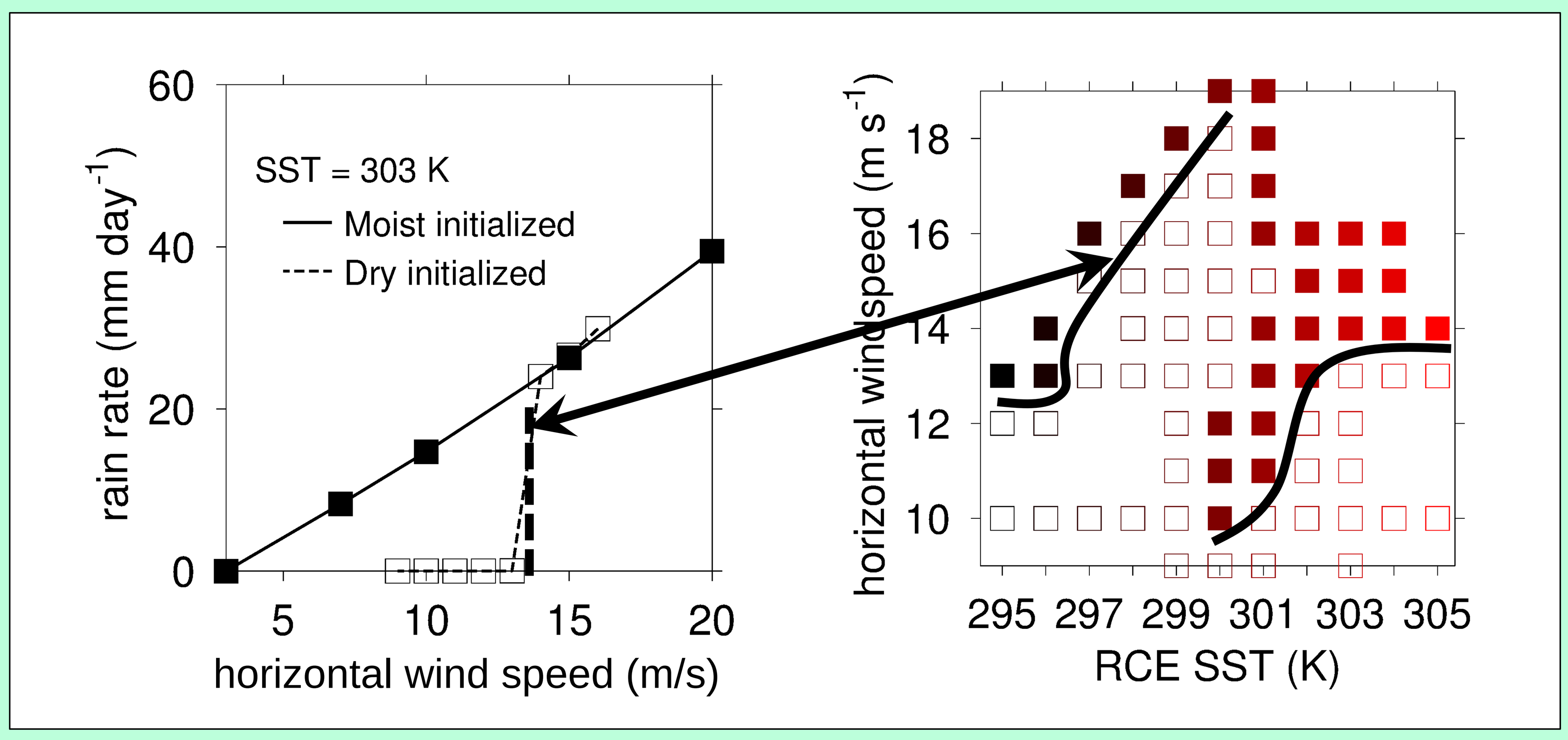

Fig.3. Multiple equilibria in precipitation (left), and the dry equilibrium as a function of horizontal wind speed and RCE SST (right; filled boxes represent a precipitating state, while empty boxes represent a non-precipitating state).

We believe that these multiple equilibria can be used to study SA in a warming climate. We hypothesize that the dry equilibrium corresponds to the dried out region of SA convection, and that the moist, precipitating, region of SA corresponds to the moist equilibrium (Fig 4).

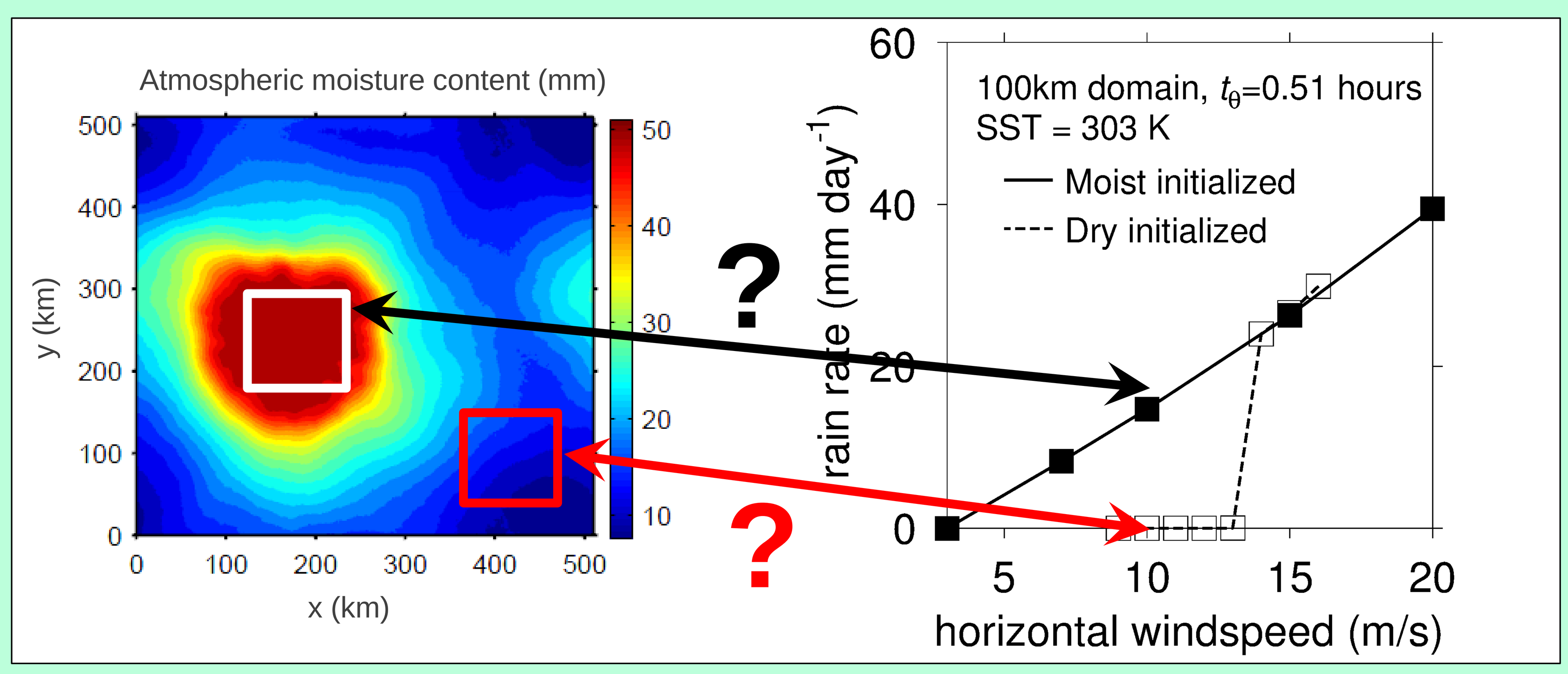

Fig.4. Does the dry area and the moist, highly precipitating, area in self aggregation correspond to the dry and moist equilibrium in weak temperature gradient simulations? The left panel presents a moisture field from a self aggregated simulation (Muller and Held, 2012).

EPILOGUE

Currently we are endeavoring to obtain self aggregation of convection in our model by running it on large domains with warm sea surface temperatures. Then we can test the hypothesis that the dry and intensely precipitating equilibrium in weak temperature gradient simulations corresponds to the aggregated and dried out regions in self aggregated convection.

- **Muller**, J. C., and I. M. Held, 2012: Detailed Investigation of the Self-Aggregation of Convection in Cloud-Resolving Simulations. *J. Atmos. Sci.*, **69**, 2551-2565, DOI: 10.1175/JAS-D-11-0257.1.
- **Raymond,** D. J., and X. Zeng, 2005: Modeling tropical atmospheric convection in the context of the weak temperature gradient approximation. *Q. J. R. Meteorol. Soc.*, **131,** 1301-1320.
- **Sessions**, S. L., S. Sugaya, D. J. Raymond, and A. H. Sobel, 2010: Multiple equilibria in a cloud-resolving model using the weak temperature gradient approximation. *J. Geophys. Res.,* **115,** D12110, 17 pp, doi:10.1029/2009JD013376.

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