The sensitivity of multiple equilibria to sea surface temperature changes in WTG simulations

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Abstract

A cloud resolving model (CRM) implementing the weak temperature gradient (WTG) approximation is used to explore multiple equilibria (precipitating and non-precipitating steady states) and their dependence on sea surface temperature.

Further, we hypothesize that there is a connection between multiple equilibria in a limited domain CRM in WTG mode, and self-aggregation of convection in radiative convective equilibrium simulations on large 3D domains.

Weak Temperature Gradient (WTG) approximation

The WTG approximation is based on the premise of horizontal homogeneity of virtual temperature in the tropics. Gravity waves are the main redistribution mechanism which enforce horizontal homogeneity. In the model, this is achieved by artificially maintaining vertical advection of potential temperature sufficient to counteract the effects of heating.

Effectively, the WTG approximation parameterizes the interaction between the large scale and the modeled convection.

Multiple Equilibria in a Cloud Resolving Model (CRM)

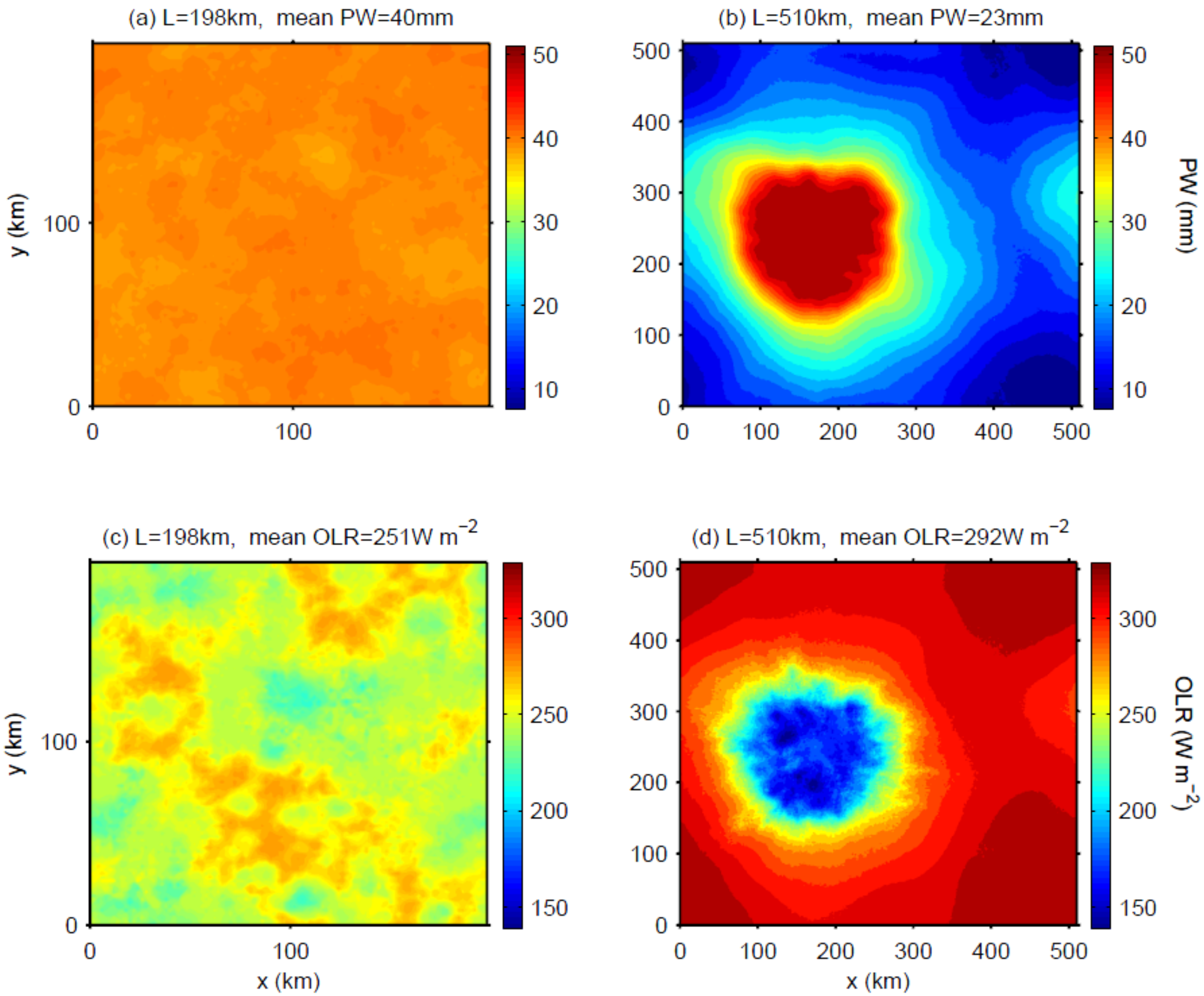
Sessions et al. (2010) investigated multiple equilibria in precipitation using a CRM. They found that imposing horizontal wind speeds smaller than a critical value resulted in two steady states (dry and precipitating) depending on the initial moisture profile. Above the critical wind speed, only the precipitating state was present.

Self-aggregation of convection

Observations show that convection has a tendency to aggregate (e.g. squall lines and mesoscale convective systems).

Muller et al. (2011) found that whether or not convection aggregates in a CRM was sensitive to domain size and grid spacing. Khairoutdinov and Emanuel (2010) found self-aggregation to be a strongly nonlinear function of the sea surface temperature.

In both investigations, the self-aggregated model runs exhibited drying of the domain, while the moisture concentrated in a sharply defined subset of the domain.



Borrowed from Muller and Held (2011)

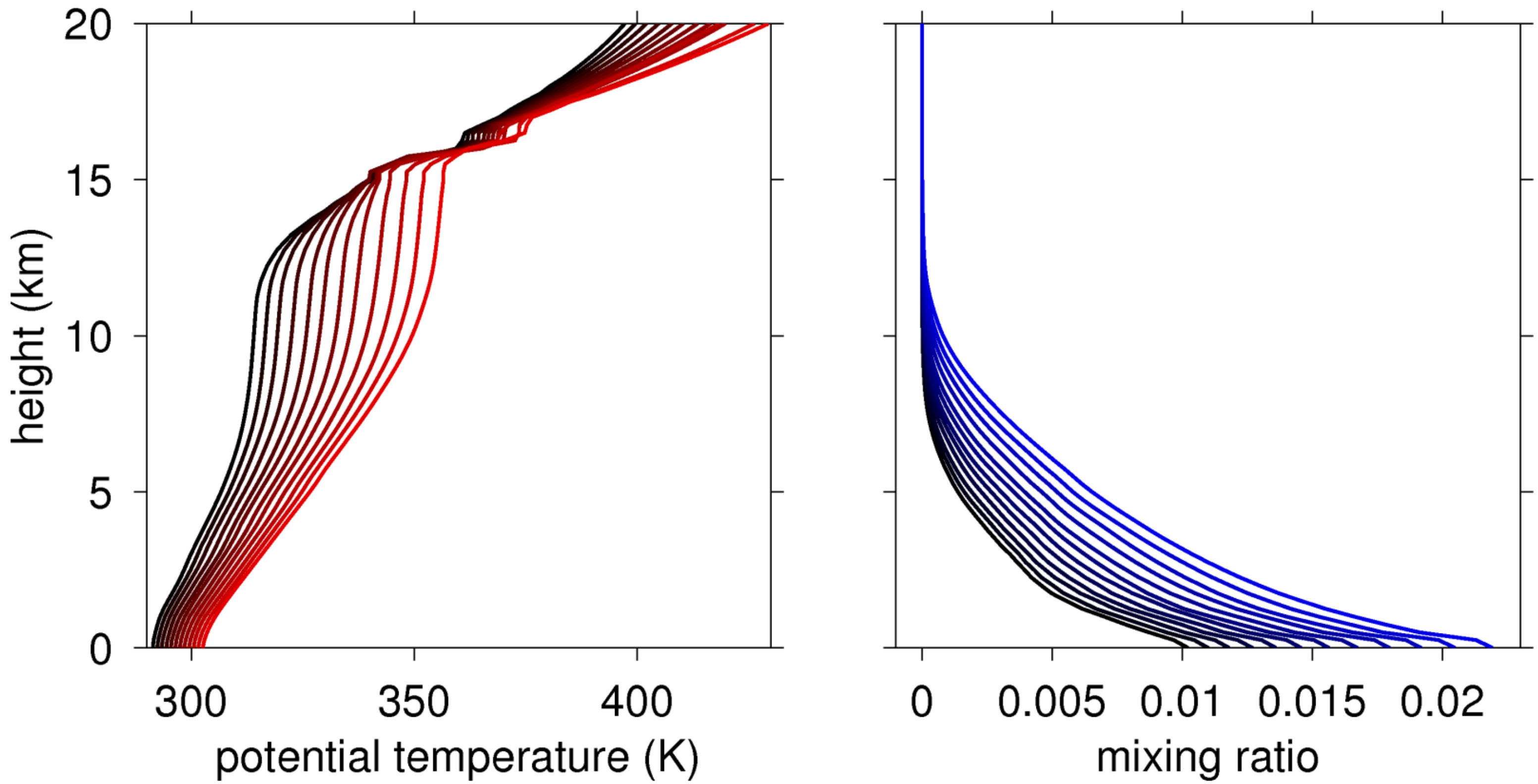
FIG. 2. Daily mean precipitable water (PW, top row) and outgoing longwave radiation (OLR, bottom row) after 60 days in two simulations with the same resolution dx = 2 km but different domain sizes L = 198 km (a,c) and 510 km (b,d). Convection self-aggregates when the domain is large enough (Fig. 1b), resulting in a moist region where convection is concentrated, surrounded by air with very dry conditions and strong longwave cooling.

Model and Method

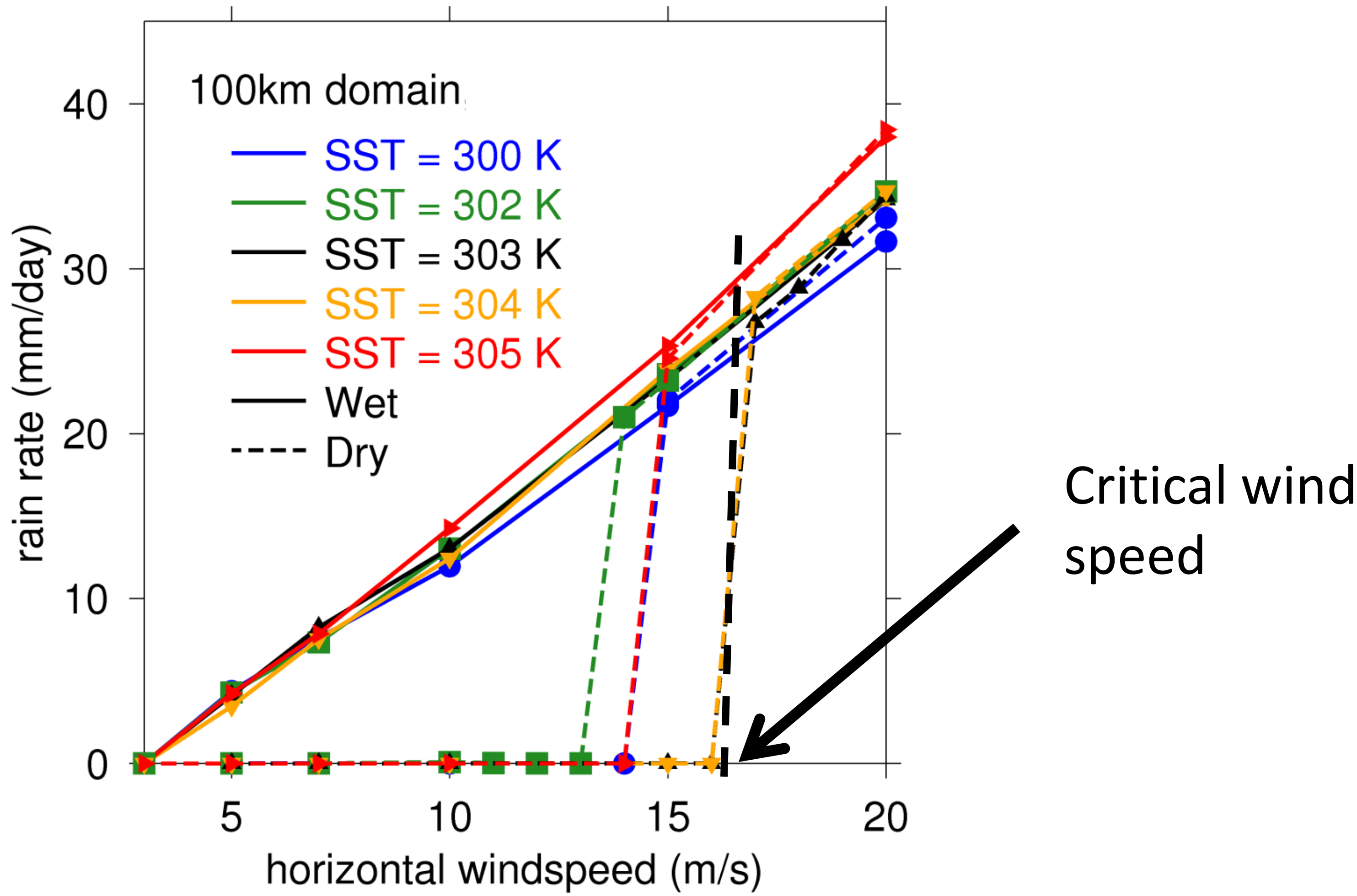
Using a CRM (Raymond and Zeng, 2005) we investigated multiple equilibria in precipitation in order to understand self-aggregation of convection.

- 100 km 2D domain
- Moisture and potential temperature reference profiles generated in radiative convective equilibrium for each sea surface temperature.
- WTG simulations for each sea surface temperature
    - Vary horizontal wind speed
    - Initialized dry or moist

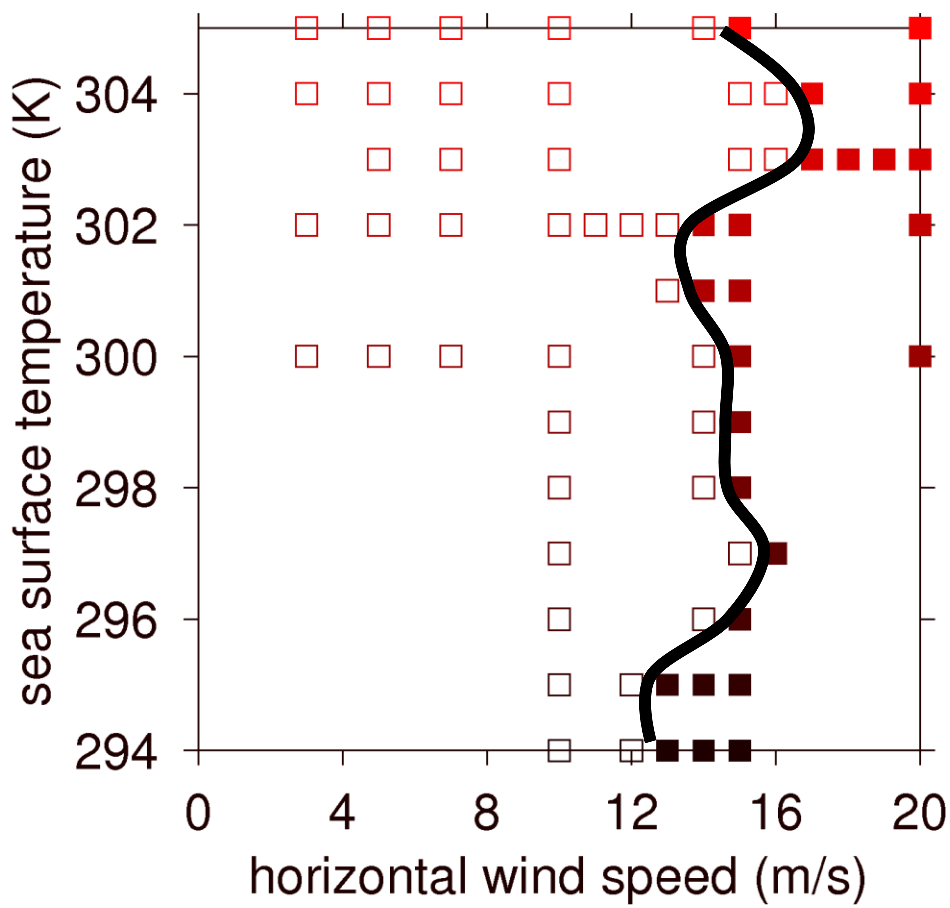
Radiative convective equilibrium reference profiles



Radiative convective equilibrium potential temperature and mixing ratio profiles with sea surface temperature from 294 to 305K. There is an increase in energy and moisture content with increasing sea surface temperatures.

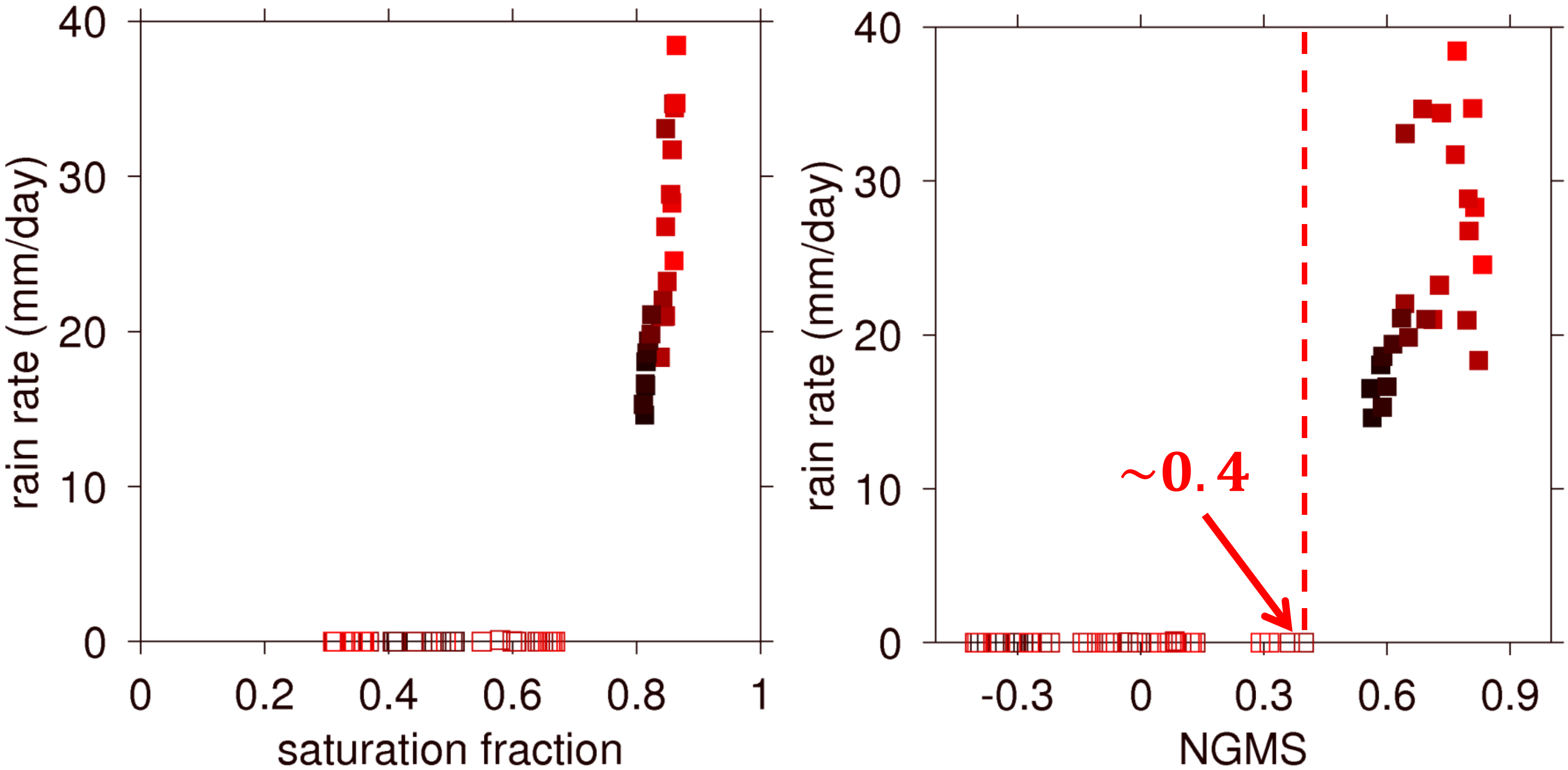


Rain rate as a function of horizontal wind speed exhibits multiple equilibrium states. The critical wind speed is clearly a nonlinear function of the sea surface temperature. Solid lines represent tests with a non-zero initial moisture profile.



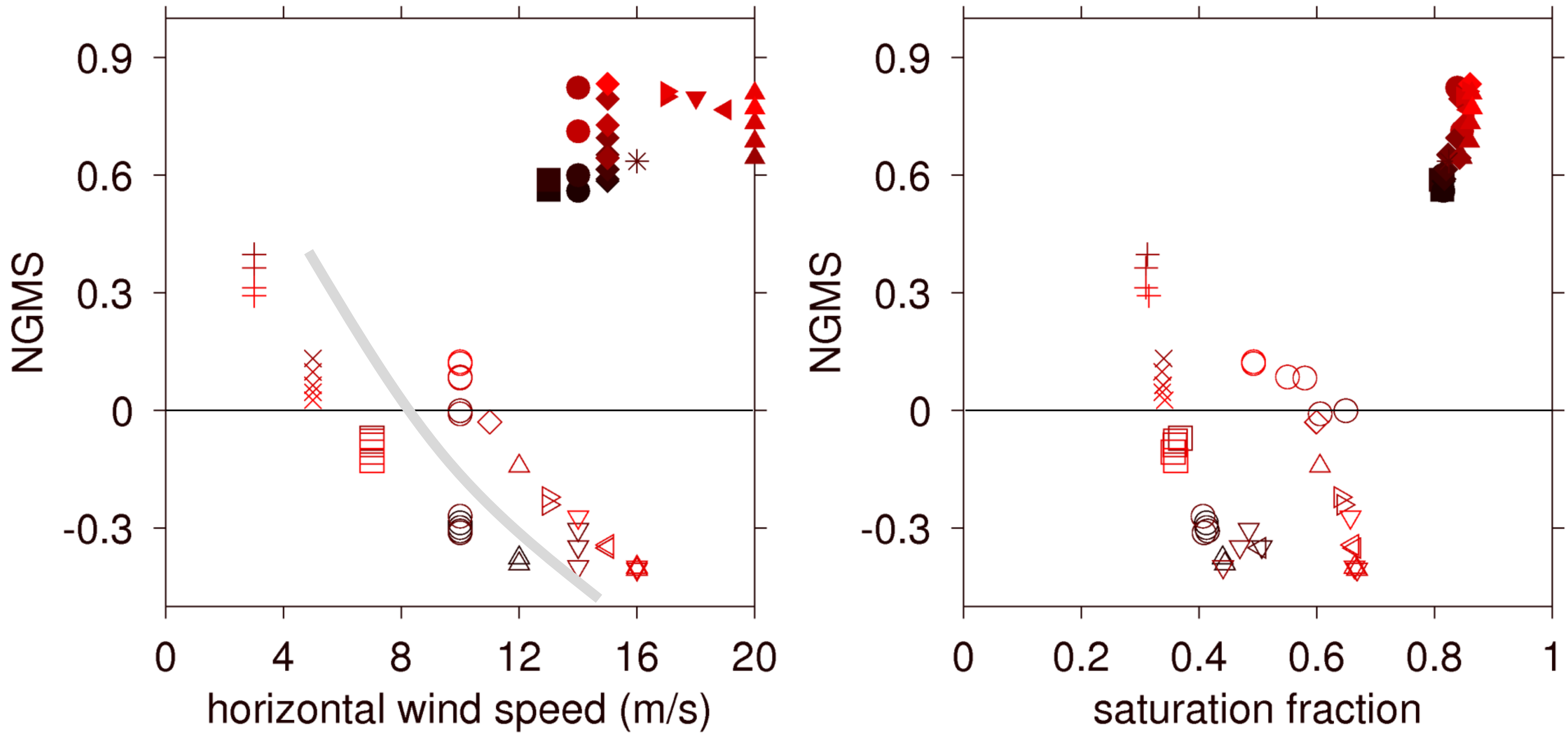
*All model runs initialized with zero moisture content

Multiple equilibrium states as a function of horizontal wind speed and the sea surface temperature. Filled (empty) symbols represent the precipitating (dry) state. Red shading increases with increasing sea surface temperature. Solid black curve approximates the critical velocity variation.



Rainfall rate as a function of saturation fraction (left) and the normalized gross moist stability (right). Note that a critical value of NGMS~0.4 separates dry and precipitating equilibria.

$$\mathrm{SF} = \frac{precipitable\ water}{saturated\ precipitable\ water}; \qquad \mathrm{NGMS} = \frac{entropy\ export}{moisture\ import}$$

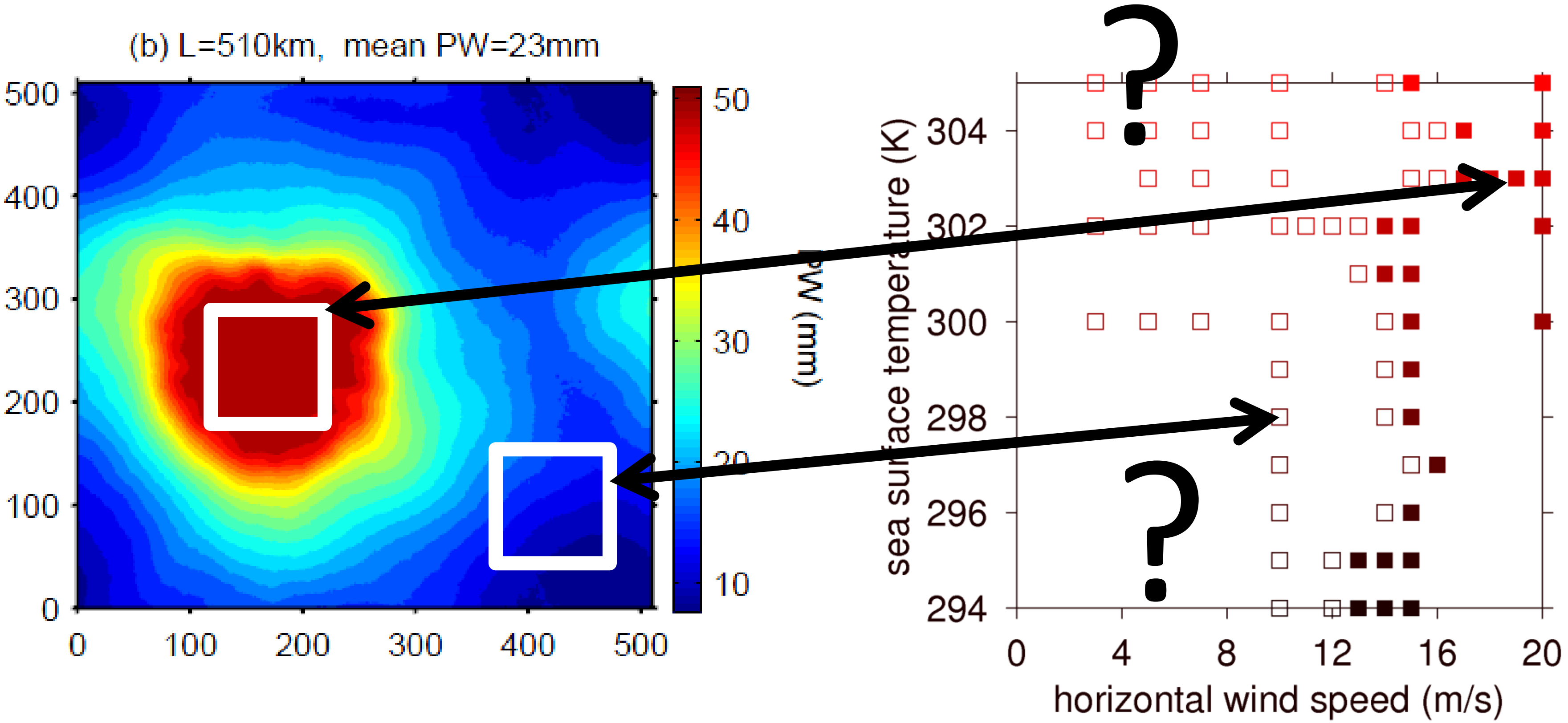


Gross moist stability as a function of horizontal wind speed (left) and saturation fraction (right). Note the discontinuity in the dry equilibrium. We hypothesize that entropy fluxes are responsible for this discontinuity.

Conclusions

- There is a strongly nonlinear dependence of multiple equilibria to sea surface temperature in our CRM in WTG mode.
- NGMS is important for the study of multiple equilibria.
- Multiple equilibria in small WTG domain may help understand self-aggregation in larger radiative convective equilibrium domain.

FUTURE WORK: Determine if the precipitating (dry) equilibrium in the 2D WTG simulations correspond to the precipitating (dried out) region in the 3D self-aggregation simulations. Positive results would give an economic tool for the study of self-aggregation.



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