Effect of a warming climate on multiple equilibria in a CRM using the weak temperature gradient approximation

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Abstract

We use the weak temperature gradient approximation to investigate the impact of a warming climate on multiple equilibria in limited domain simulations. Multiple equilibria refers to the existence of a precipitating and non-precipitating steady state in identical environmental conditions, but different initial conditions. A warming climate is modeled by increasing sea surface temperatures in radiative convective equilibrium simulations used to represent the large scale environment.

We find that changes in temperature and moisture reference profiles compete to influence the range of multiple equilibria. By individually varying the changes in potential temperature and moisture reference profiles, we find that either increasing stability or moisture in reference profiles reduces the range of multiple equilibria.

Weak Temperature Gradient (WTG) Approximation

In the tropics, we assume that gravity waves quickly and efficiently redistribute buoyancy anomalies, leaving a weak horizontal temperature gradient. In the model, this is achieved by relaxing local perturbations in potential temperature to a reference profile. This way we parameterize the large scale in limited domain simulations. Reference temperature and moisture profiles are obtained from radiative convective equilibrium (RCE) simulations with different sea surface temperatures (SST).

RCE reference profiles used in this study are shown in **Figure 1**.

Instability Index and Saturation Fraction

Instability Index is defined as:

$$II = s_b - s_t,$$

where s_b and s_t are the domain and time averaged saturated moist entropy from 1 to 3 km, and 5 to 7 km, respectively. Higher instability index reduces precipitation efficiency.

Saturation Fraction is defined as:

$$SF = \frac{precipitable\ water}{saturated\ precipitable\ water}.$$

Figure 2 shows the instability index and saturation fraction for the reference temperature and moisture profiles from Figure 1. We notice that the value of each increases for warmer SSTs.

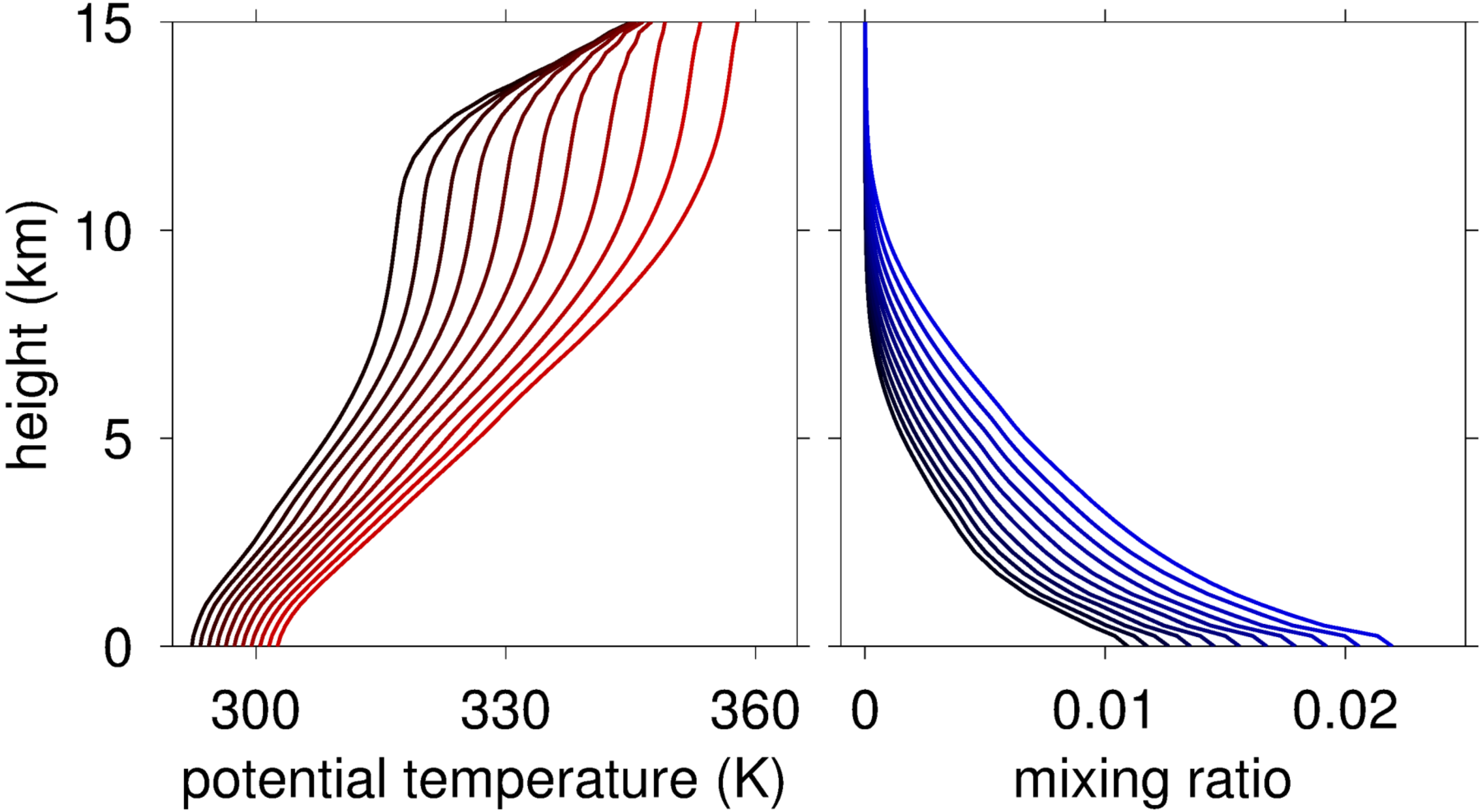


Figure 1: Radiative convective equilibrium profiles of potential temperature (left) and mixing ratio (right), with sea surface temperature from 295 to 305 K (increasing shade). Strong warming and moistening of the middle troposphere is noticeable for higher sea surface temperatures.

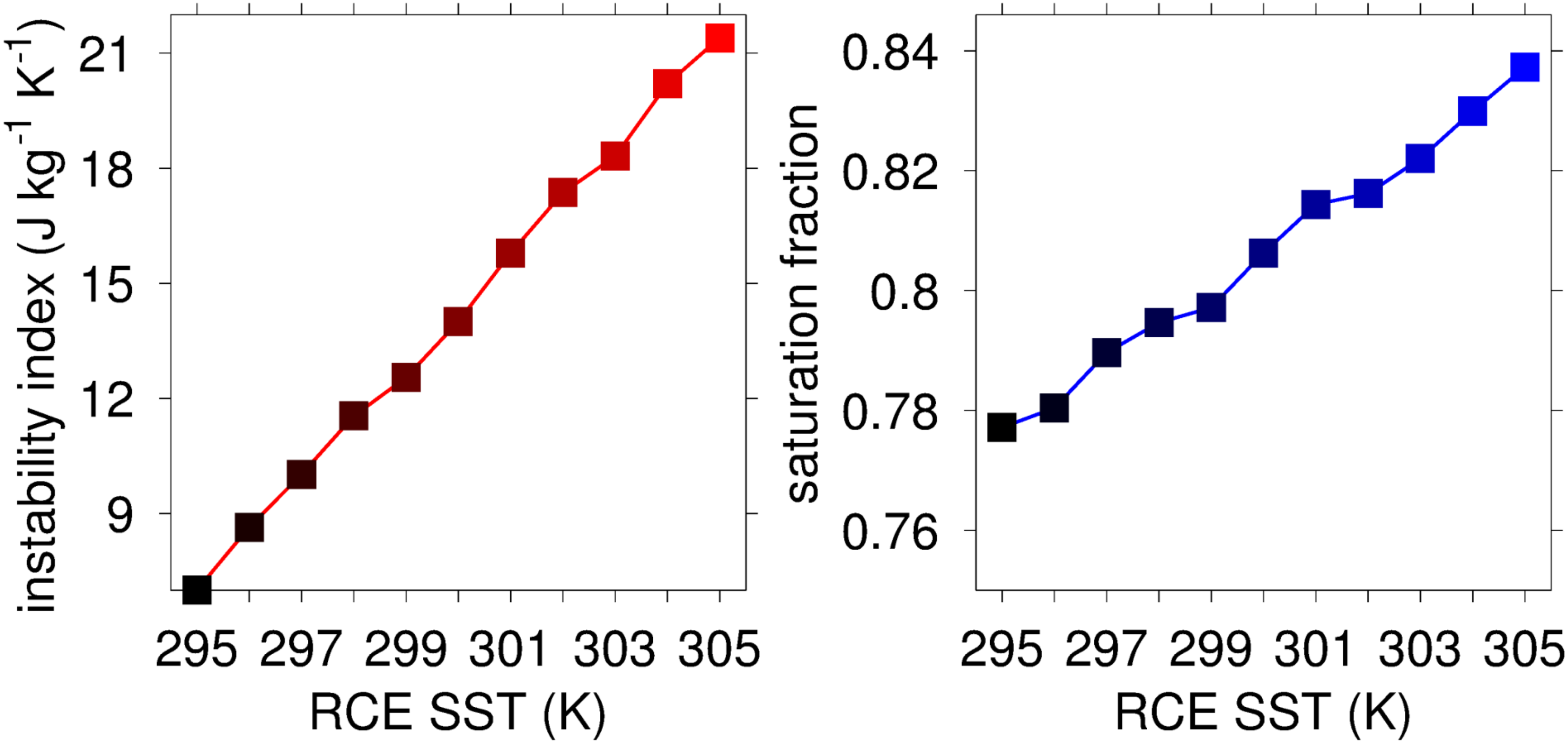


Figure 2: Instability index (left) and saturation fraction (right) of the radiative convective equilibrium profiles from Figure 1. We notice a destabilization and moistening with increasing sea surface temperatures.

Multiple Equilibria in Precipitation

Sessions et al. (2010) found multiple equilibria in precipitation in the model of Raymond and Zeng (2005). Multiple equilibria are defined as a precipitating and non-precipitating steady state for the same boundary conditions but with moist or dry initial conditions. The authors varied horizontal wind speed, and found that after a critical wind speed multiple equilibria would be replaced by a single, precipitating equilibrium (**Figure 3**). Here, we study the effect of SST changes on the range of multiple equilibria.

Figure 4 shows the precipitating (solid symbol) and non-precipitating dry initialized simulations as a function of horizontal wind speed and SSTs. We notice a highly nonlinear behavior of the critical horizontal wind speed with SST changes.

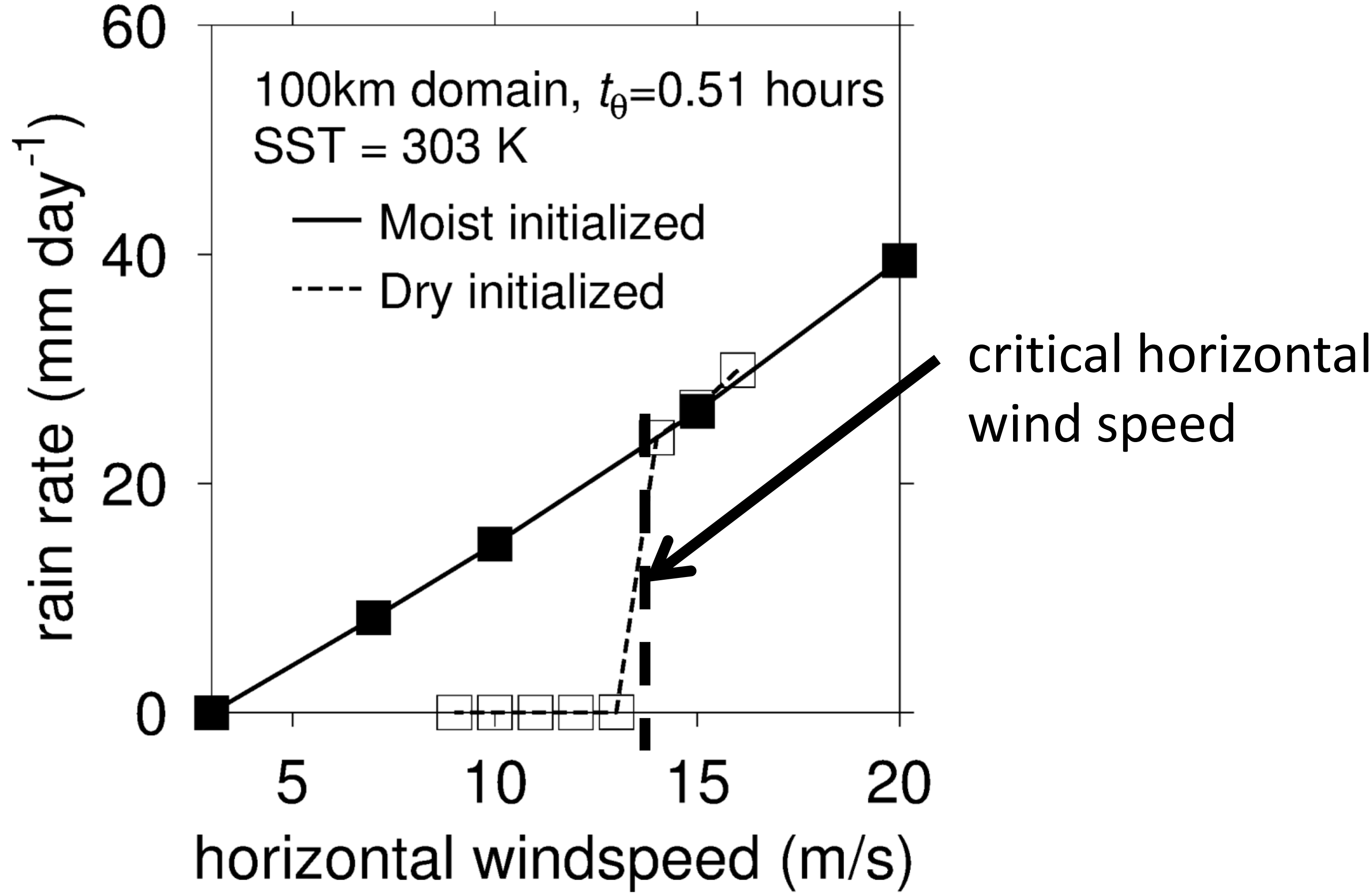


Figure 3: Moist (solid line, filled symbols) and dry (dashed lines, empty symbols) initialized weak temperature gradient simulations as a function of horizontal wind speed. We notice multiple equilibria until 13.5 m/s, and a single equilibrium thereafter.

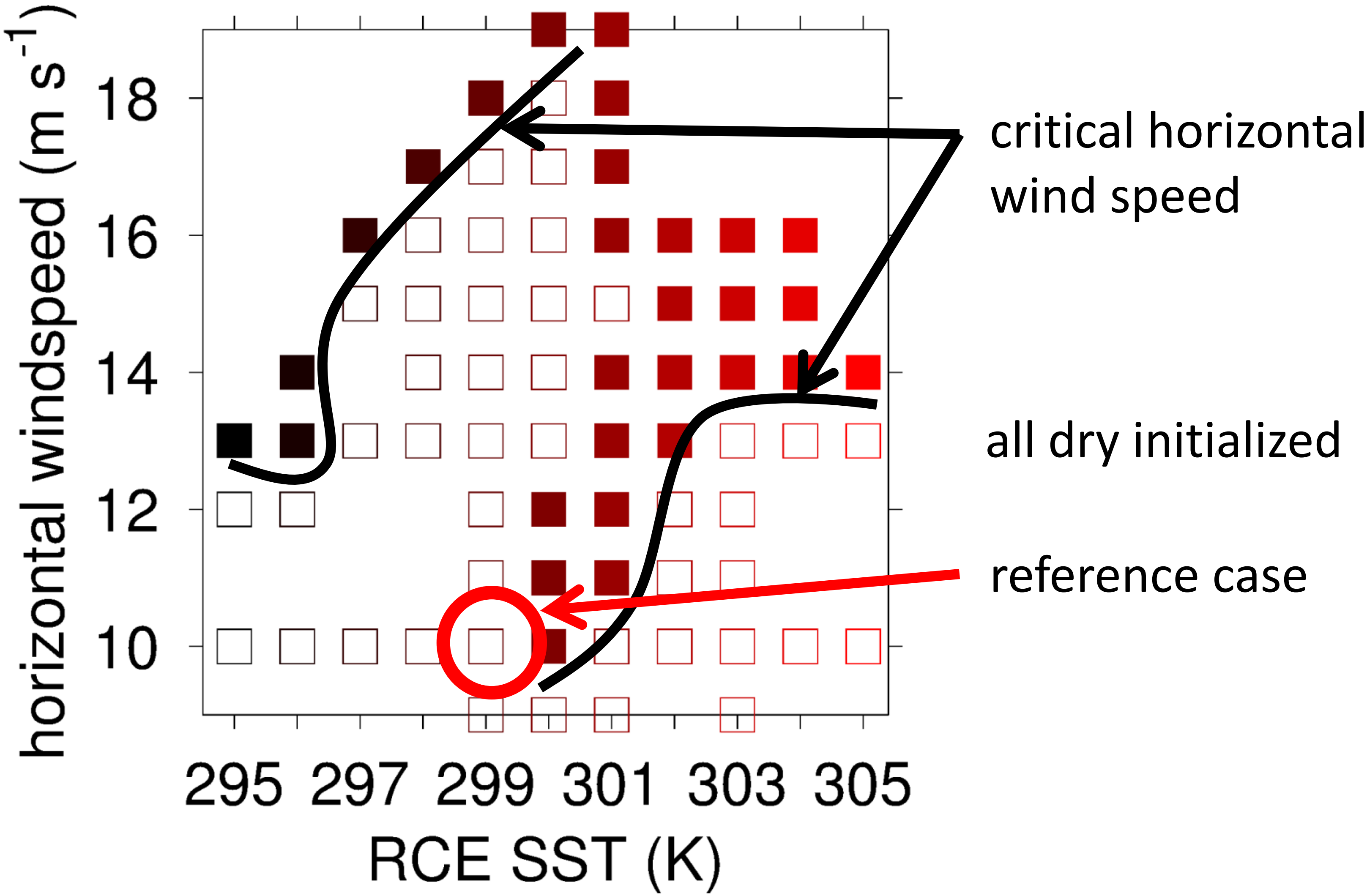


Figure 4: Precipitating (filled symbols) and non-precipitating (empty symbols) dry initialized WTG simulations as a function of horizontal wind speed and SSTs. Strong nonlinear behavior in critical wind speed with SSTs (see text) is obvious.

Effects of stability and humidity changes on multiple equilibria

We check the relative influence of stability and tropospheric humidity for a reference case (see Figure 4, red circle), by independently varying the RCE reference temperature and moisture profiles.

Rain rate is shown in **Figure 5** where red symbols represent the rain rate where we fixed the moisture profile and varied the temperature profile (i.e. instability index), and blue symbols represent the rain rate where we fixed the temperature profile and varied the moisture profile (i.e. saturation fraction).

We notice that increasing the stability or saturation fraction both destroy the dry equilibrium.

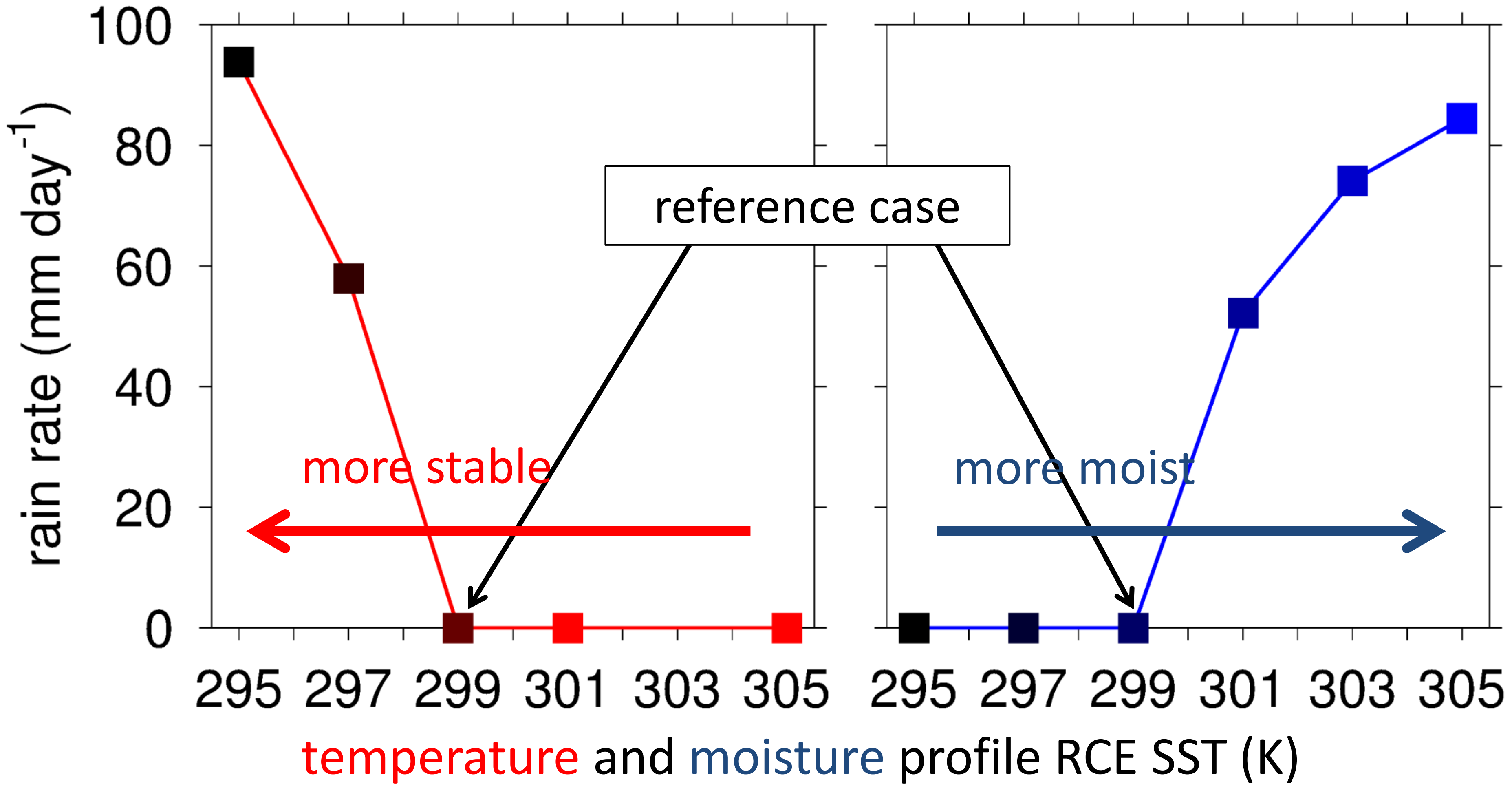
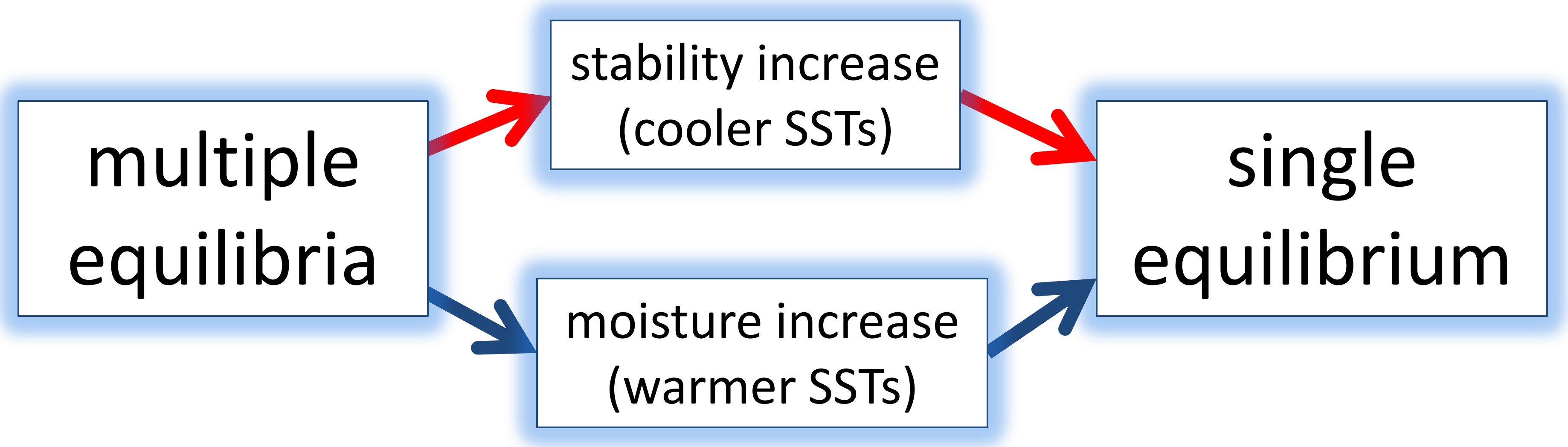


Figure 5: WTG simulation rain rates for cases where moisture profile is fixed and temperature profile (i.e. instability index) is varied (left), and cases where temperature profile is fixed and moisture profile (i.e. saturation fraction) is varied.

Conclusions

By independently varying the reference instability index and saturation fraction in WTG simulations we find that in a warming climate, the stability and moisture of the large scale environment compete to influence the range of multiple equilibria. A more stable atmosphere and a more moist atmosphere destroy the dry equilibrium.



References

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**, pp. 1301–1320, doi: 10.1256/qj.03.97.

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, doi:10.1029/2009JD013376.

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