Parameterizing large-scale circulations based on the weak temperature gradient approximation

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and thanks to GASS WTG project participants

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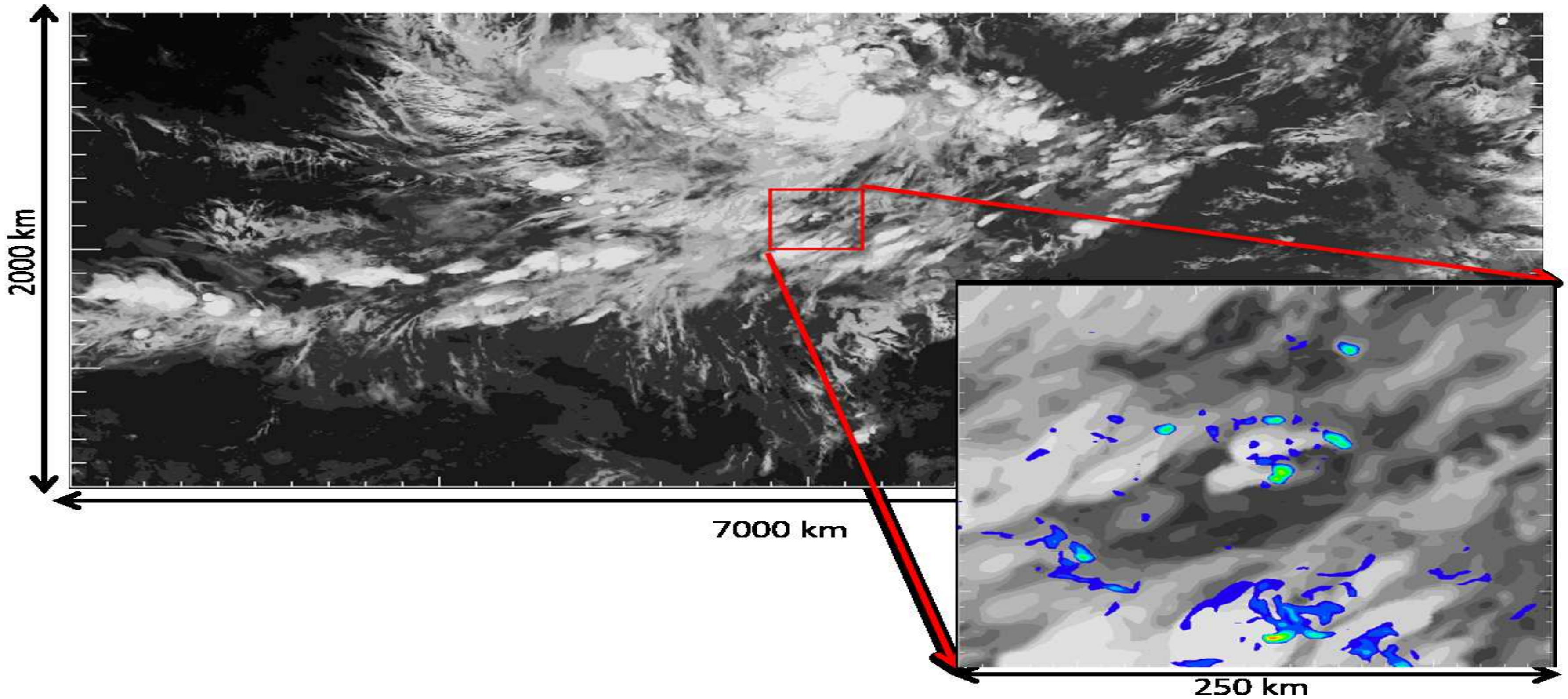
Overview

- Weak temperature gradient parameterization: how it works
- Circulations in a homogeneous environment
- Circulations in an inhomogeneous environment
- Transitional cases and parameterization testing

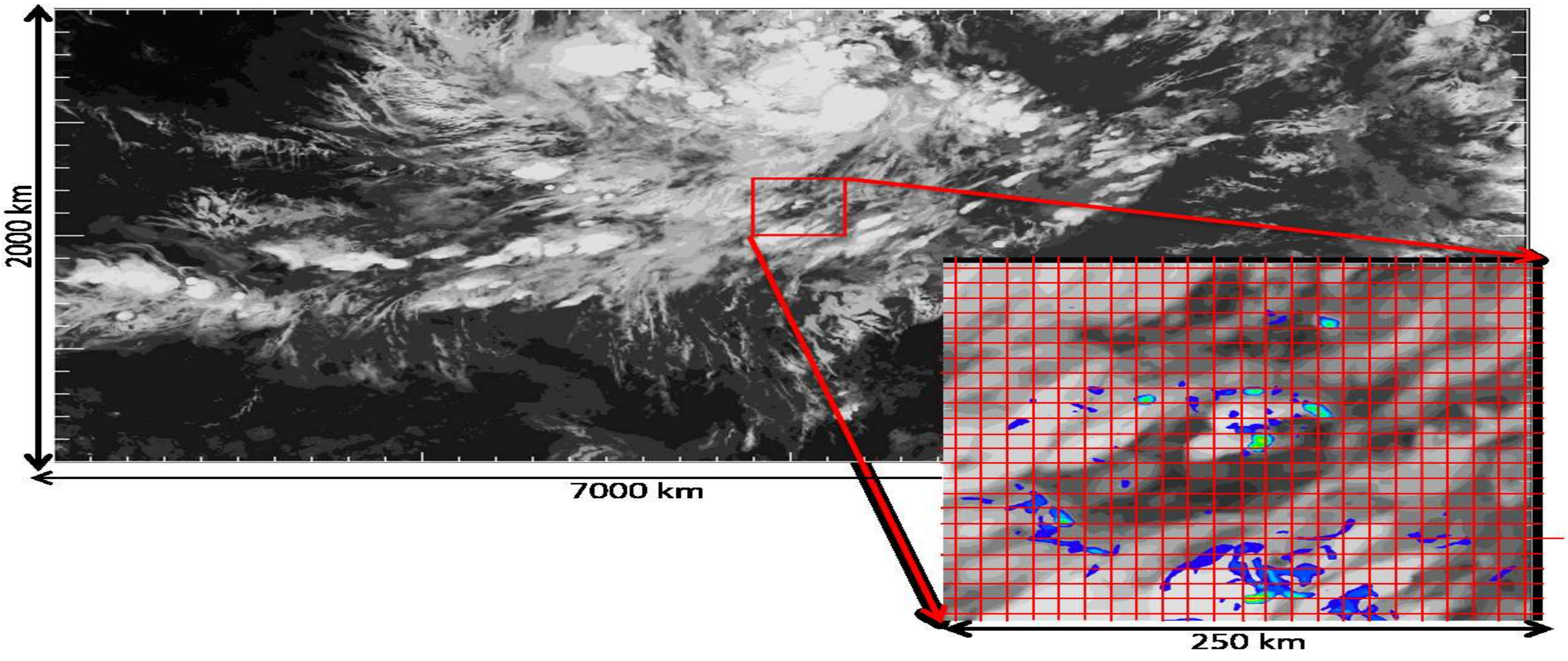
Weak temperature gradient parameterization: how it works

Scale difference problem



- Difficult to parameterize the sub-grid convective activity in a GCM

Scale difference problem

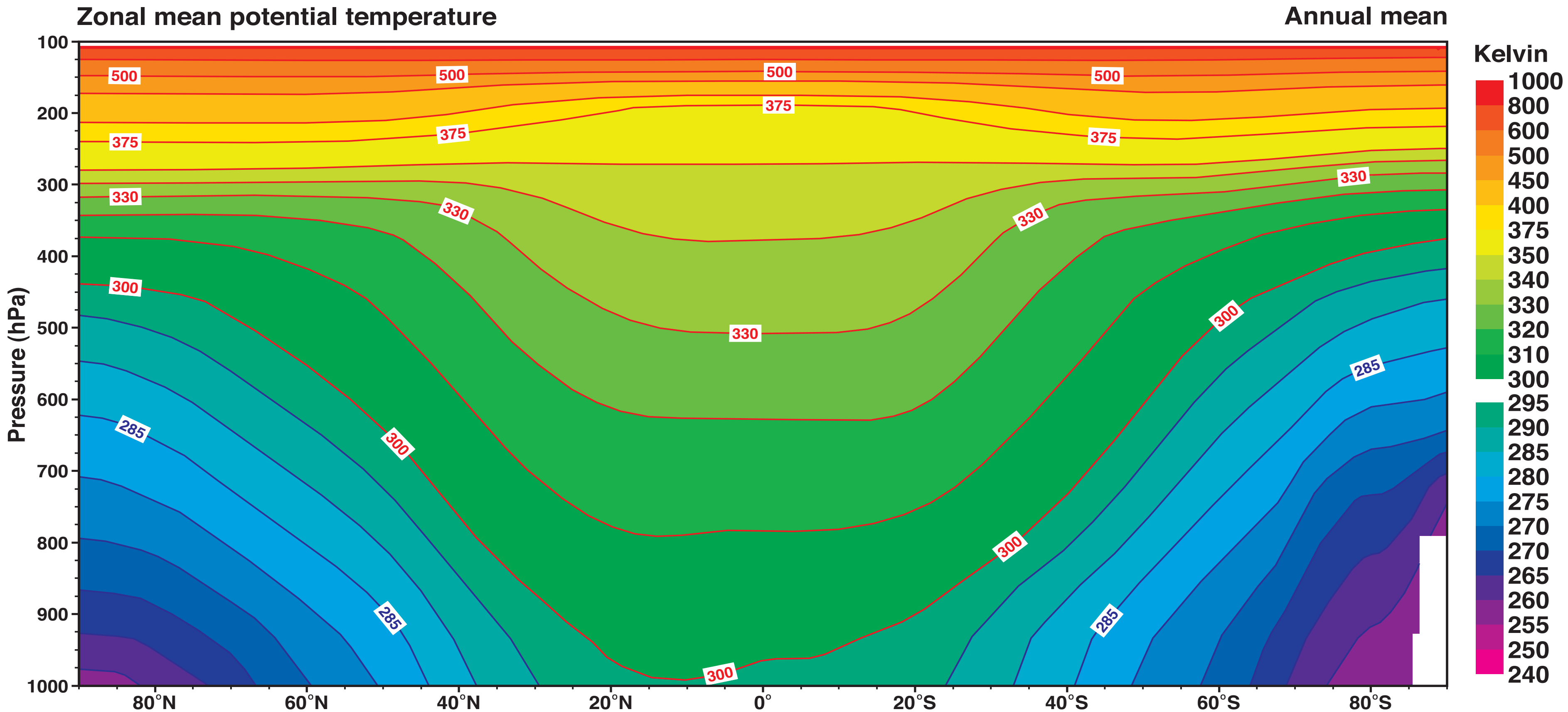


- Simulations which well resolve the convective activity typically neglect, or prescribe, motions on scales larger than the domain

Modelling approaches

- Large-domain and high-resolution simulations
- GCM: simulate the large-scale circulation but parameterize the convection
- CRM: impose the large-scale circulation and simulate the convection
- SCM: impose the large-scale circulation and test parameterization of the convection (too easy?)
- Today: parameterize the large-scale circulation and simulate the convection
- Also: parameterize the large-scale circulation and parameterize the convcetion

Weak temperature gradients



- Little variation in free troposphere over the tropics

Basic ideas

- Gravity waves are effective in redistributing density anomalies so as to maintain near uniform density on isobaric surfaces
- This leads to large-scale circulations which act to balance local anomalies of heating so as to produce quasi-uniform potential temerature
- The boundary layer is different because conditions there are tied to the local underlying surface temperature

Diagnosing circulations

$$\frac{\partial\theta}{\partial t} + \mathbf{v}\nabla_h\theta + w\frac{\partial}{\partial z}\theta = S \qquad (1)$$

On the large scale, simplify to

$$\overline{w}\frac{\partial}{\partial z}\overline{\theta} \approx \overline{S} = Q_R + Q_c \qquad (2)$$

- Based on $\overline{S}$, can evaluate the $\overline{w}$ required for the WTG balance
- Can enforce Eq. 2 by resetting $\theta(t,z) = \theta(z)$, and allow the diagnosed $\overline{w}$ to produce a source/sink term in moisture equation (Sobel and Bretherton, 2000)
- $\theta(z)$ typically taken from RCE

Relaxation form

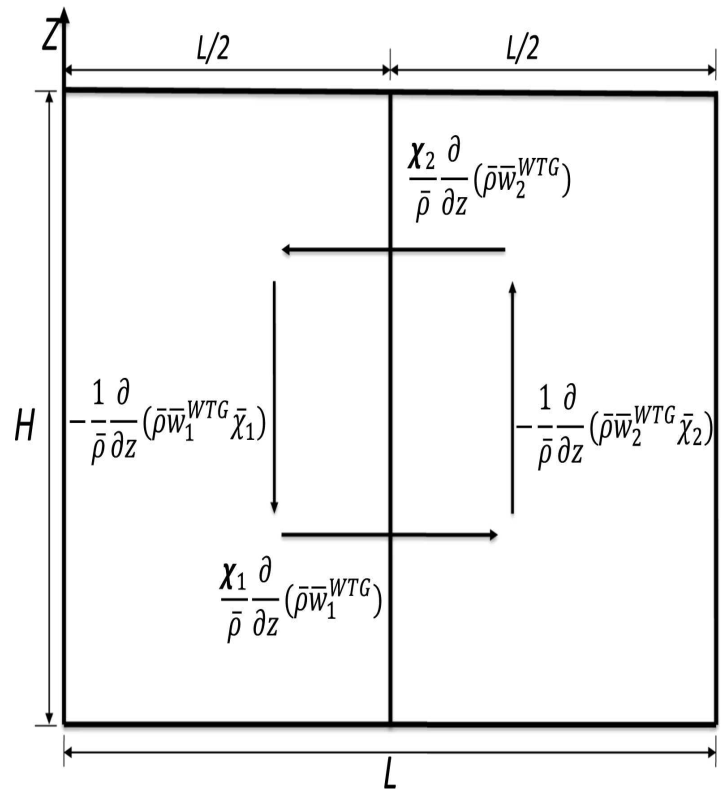
A weaker version envisages gravity waves reducing temperature difference over a finite timescale τ,

$$\overline{w}\frac{\partial}{\partial z}\overline{\theta} = \frac{1}{\tau}(\overline{\theta} - \overline{\theta}_{\mathrm{ref}}) \qquad (3)$$

(Raymond and Zeng, 2005)

- τ is of order a few hours, corresponding to lengthscales of order 1000 km for gravity waves of order 50 ms^{-1}
- Reference state typically taken from RCE
- The RCE surroundings do not vary in response to the WTG-derived circulation

Generalize to two regions



- Reference state imagines open system with coupling to infinite reservoir
- Consider two regions with a diagnosed circulation affecting both
- Allows study of influence of remote changes on local convection

Generalization to two regions

$$\overline{w}_2 \frac{\partial}{\partial z}\overline{\theta}_2 - \overline{w}_1 \frac{\partial}{\partial z}\overline{\theta}_1 = \frac{1}{\tau}(\overline{\theta}_2 - \overline{\theta}_1) \tag{4}$$

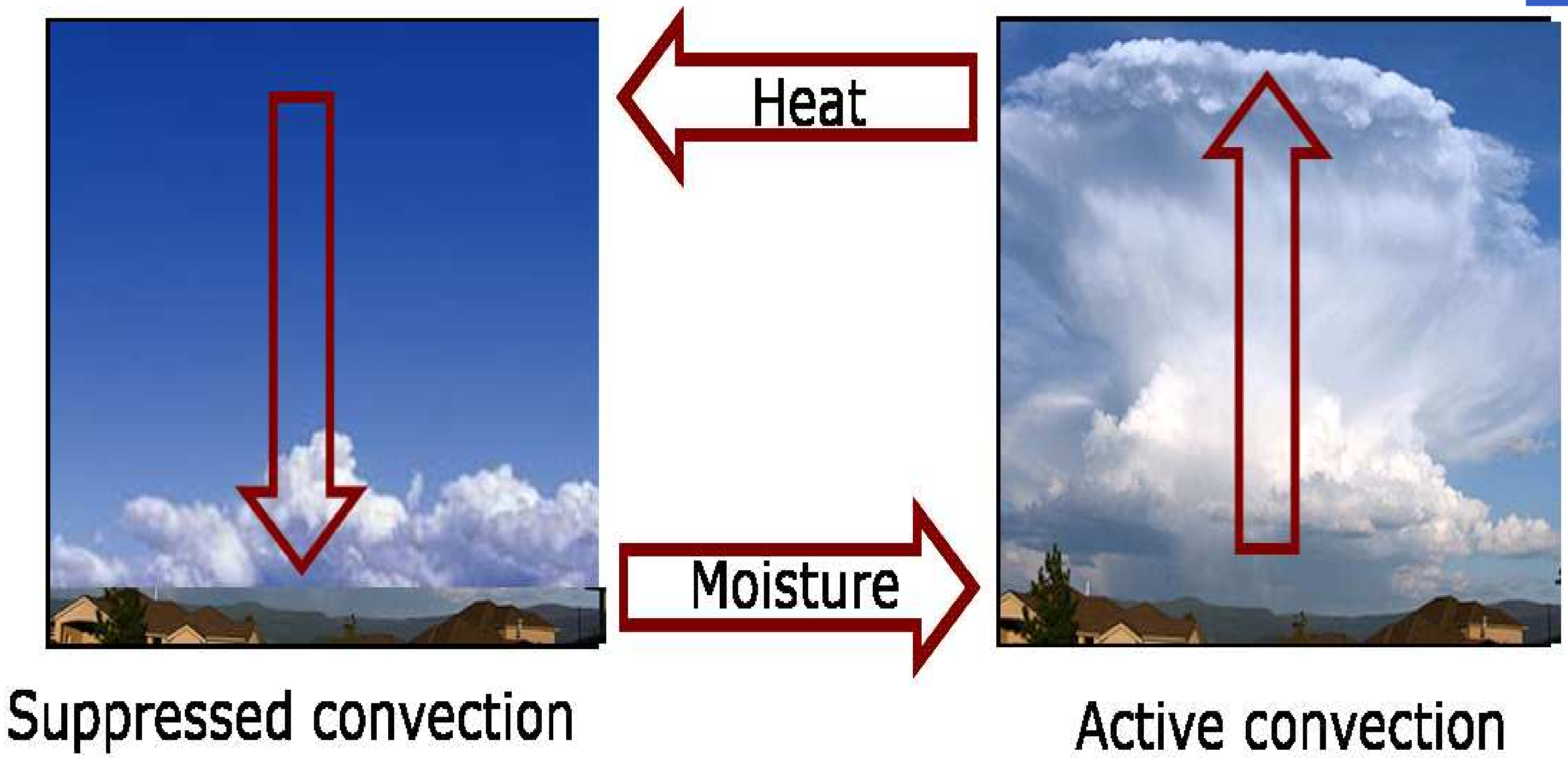
For continuity

$$(1-\varepsilon)\overline{w}_1 + \varepsilon\overline{w}_2 = 0 \tag{5}$$

leading to

$$\overline{w}_1 = \frac{1}{\tau}\left[\frac{\overline{\theta}_1 - \overline{\theta}_2}{\frac{\partial\overline{\theta}_1}{\partial z} + \left(\frac{1-\varepsilon}{\varepsilon}\right)\frac{\partial\overline{\theta}_2}{\partial z}}\right] \tag{6}$$

Recovers reservoir formula for relative area $\varepsilon \longrightarrow 0$ or 1.



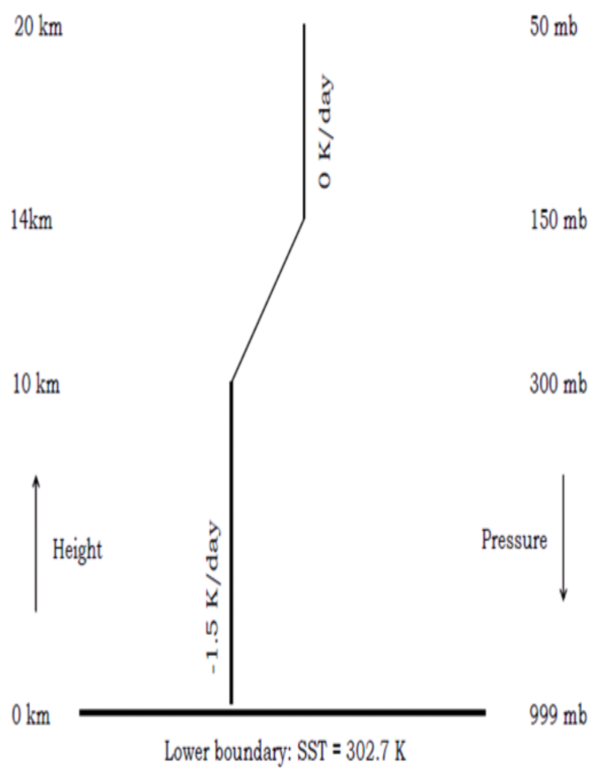
- We also associate a horizontal WTG velocity with $\overline{w}_{\mathrm{wtg}}$ in order to close the circulation
- This gives a closed two-region approach constrained by energy and moisture conservation

Treatment of boundary layer

- Boundary layer conditions tied to the local SST
- Treament is to calculate w_{WTG} for heights above some nominal BL top, say 1.5km, and linearly interpolate between $w_{\mathrm{WTG}}(z_{\mathrm{BL}})$ and $w_{\mathrm{WTG}}(z = 0) = 0$
- We will return to this...

Circulations in a homogeneous environment

Models used



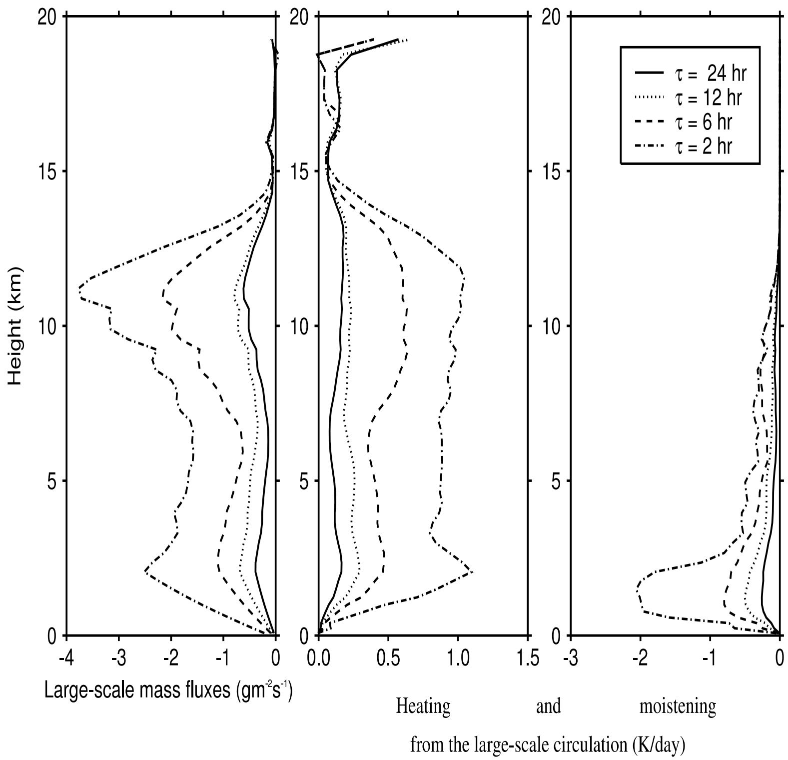
- Run to equilibrium with prescribed radiative cooling
- Typically for 40 days, with first 20 discarded as spin-up
- Using LEM, 2D with $\Delta x = 500$ m
- Also use some GASS WTG intercomparison results for reference-state cases

Reference state, same SST

- Generate RCE reference state
- Make a WTG coupling to this state with simulated region initialized to the RCE state
- Use identical forcing and surface conditions to the RCE configuration
- What happens?

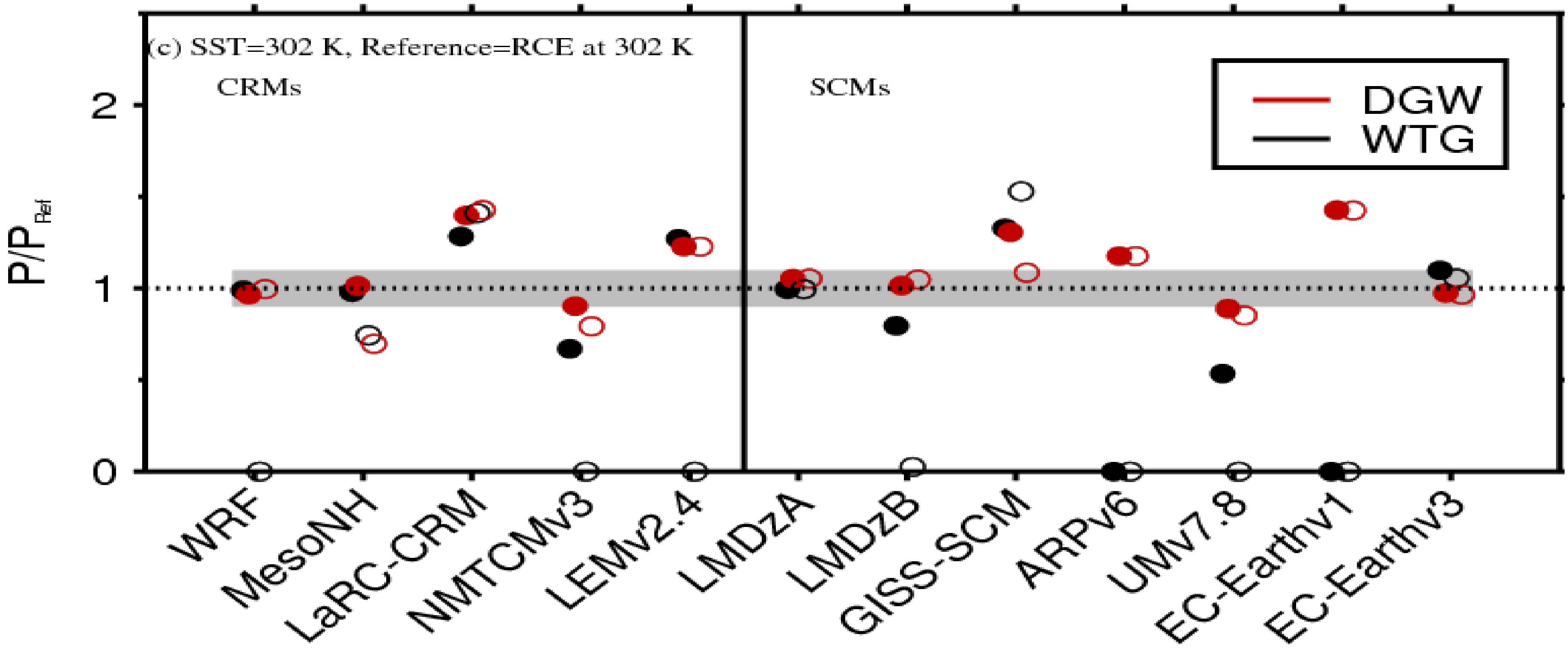
Reference state, same SST

- Descent in simulated region with associated heating and drying tendencies



mm/d	Rain	Evap
RCE	4.77	4.80
$\tau = 120$ h	4.70	4.74
$\tau = 24$ h	4.40	4.77
$\tau = 12$ h	4.03	4.78
$\tau = 6$ h	3.43	4.64
$\tau = 2$ h	1.99	4.47

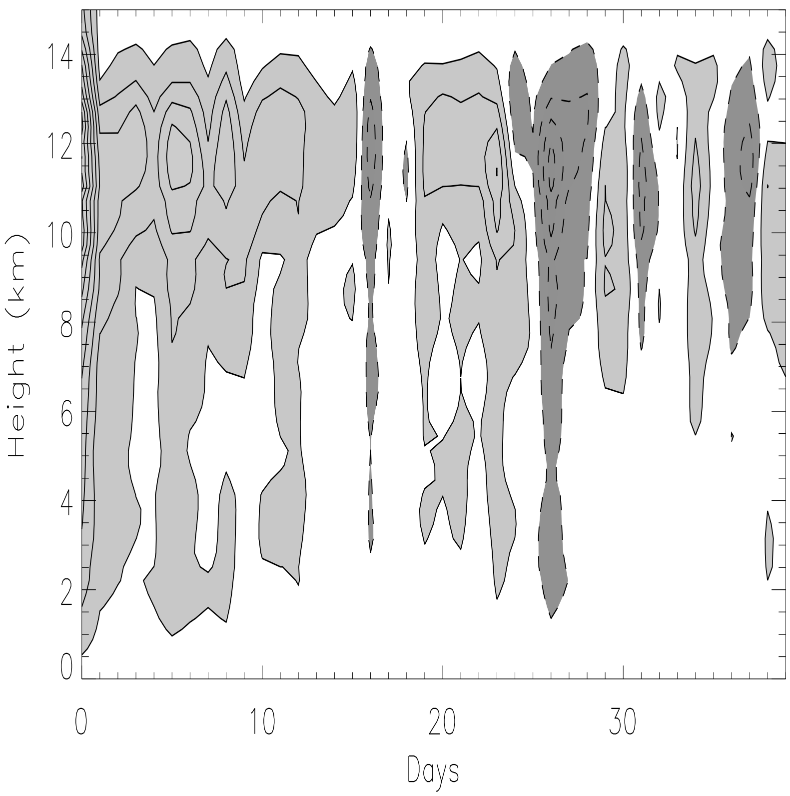
Other models



- Some develop large-scale circulations within a homogeneous environment
- Some support multiple equilibria

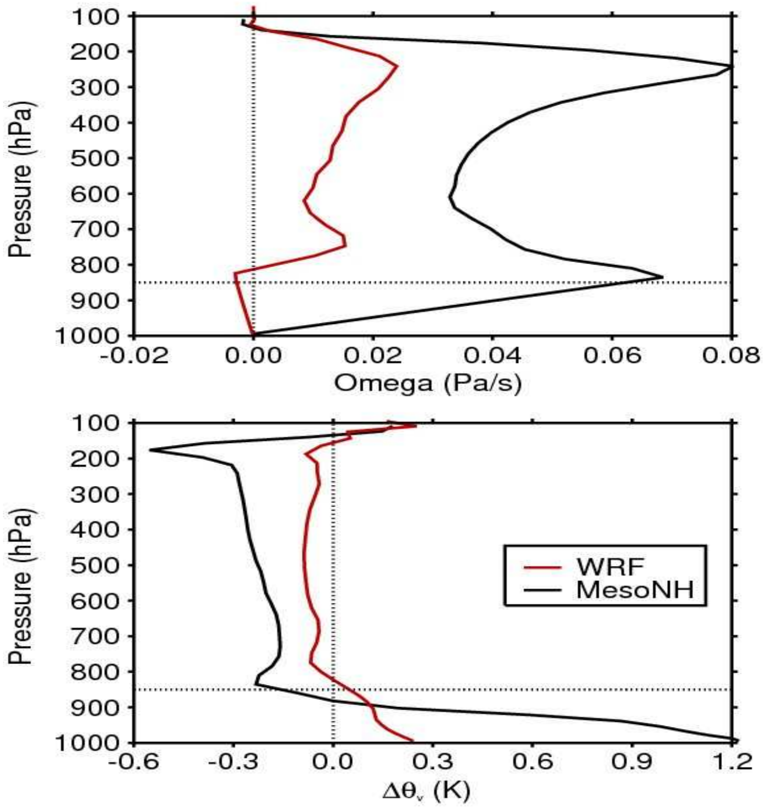
Two region configuration

- Produces no time-mean WTG circulation irrespective of ε
- Adjustment to equilibrium much slower for small ε
- But note small ε qualitiatively different from reference configuration



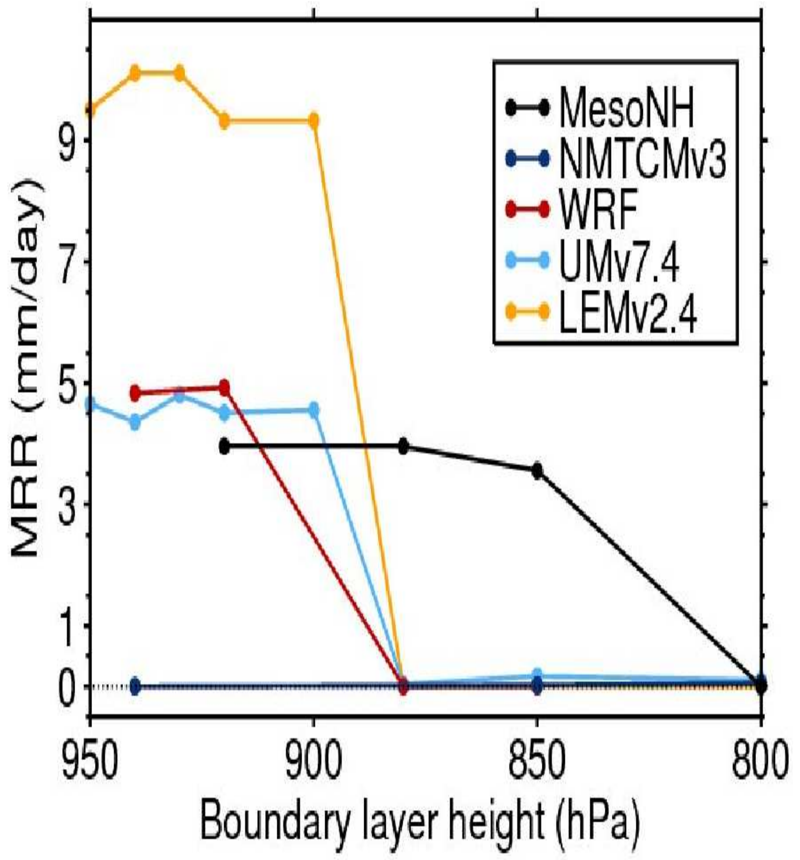
Role of Boundary Layer Top

- Consider w_{WTG} profiles in cases of dry equilibria
- Change of sign can occur close to BL top
- Sign may differ from that which would have been expected without the linear interpolation prescription



Varying the Boundary Layer Top

- Critical BL depth to get the dry state: equilibrium state can be made precipitating by setting a lower depth (but still above mixed layer)
- Some dependence of multiple states on SST (more likely if higher) and τ (more likely if shorter)



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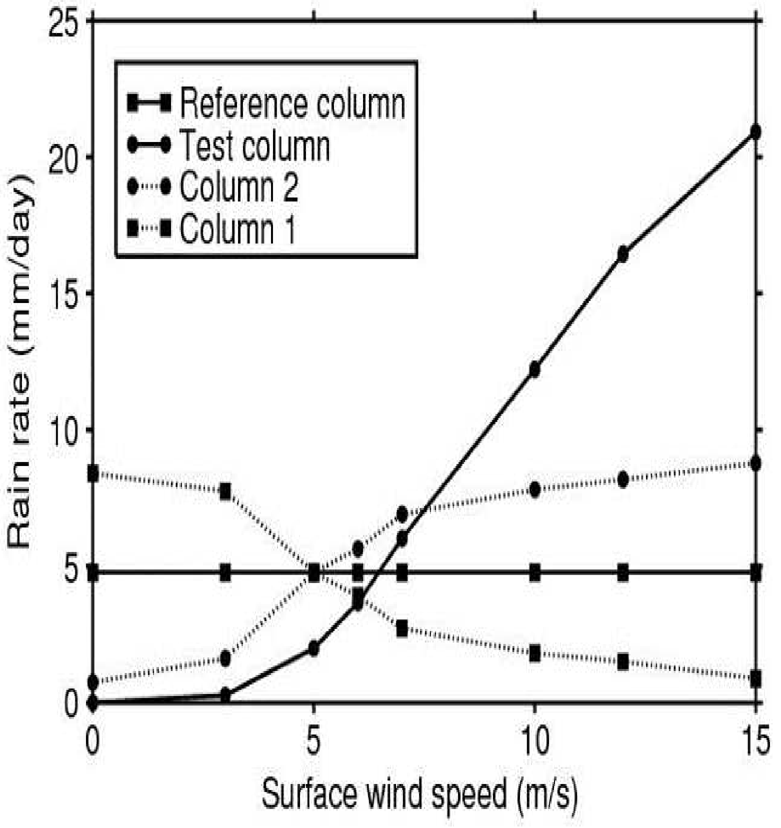
Circulations in an inhomogeneous environment

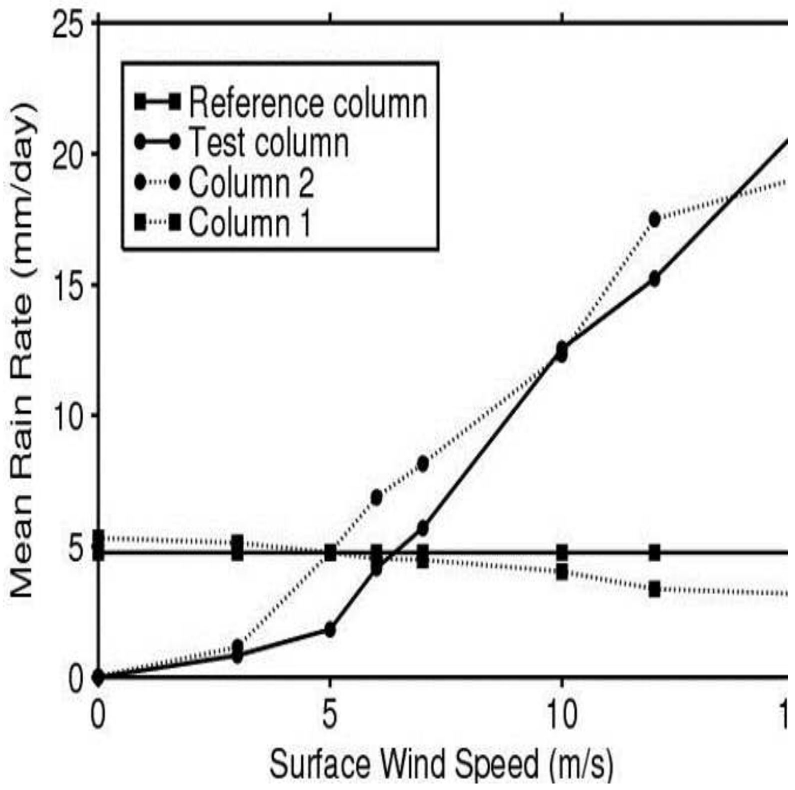
Precipitation variations

- Vary surface wind speed with $\tau = 2$ h for reference column case and for $\varepsilon = 0.5$
- Two region case less sensitive due to constraints from closed budgets



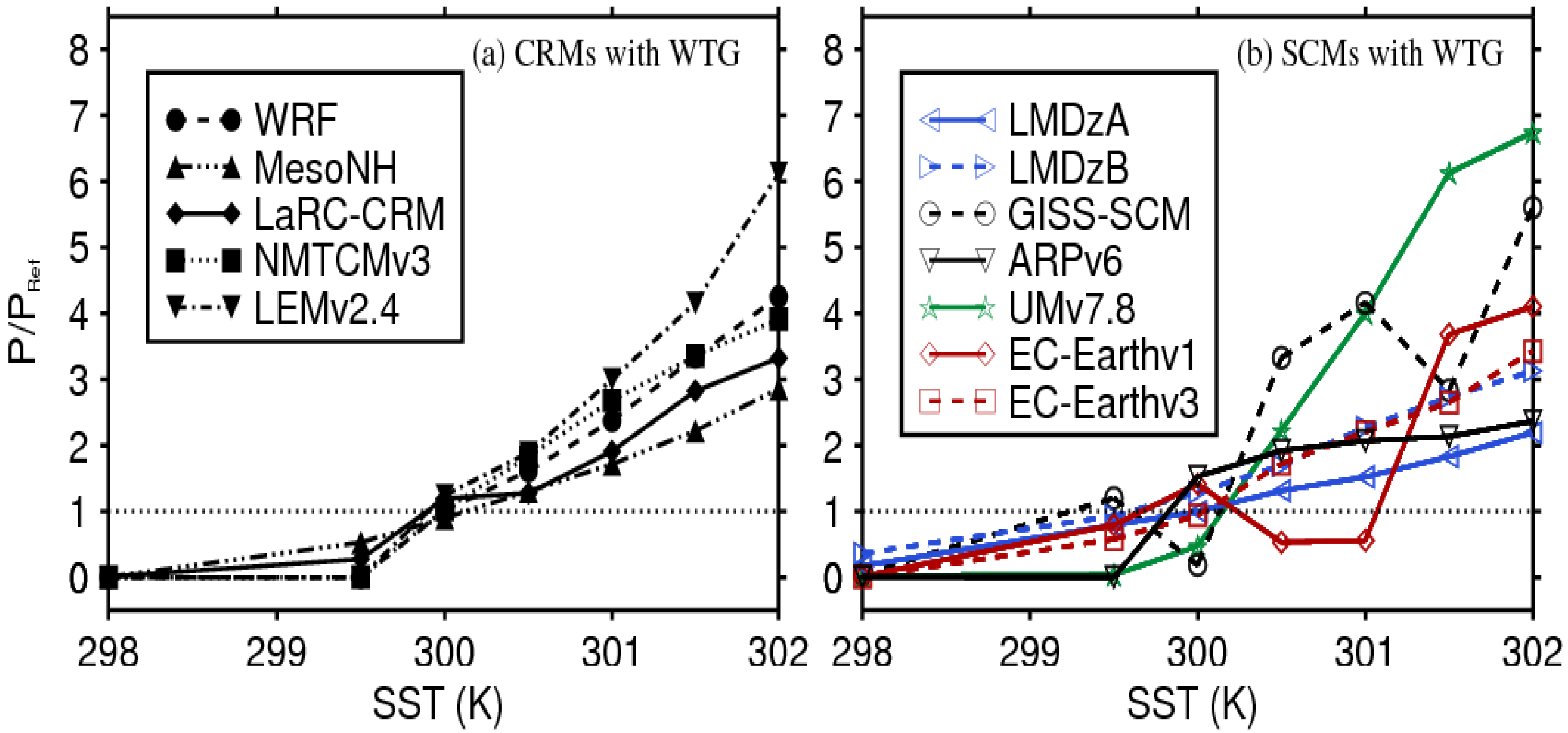
Precip variations for small ε

- Comparison against $\varepsilon = 0.1$ and $\tau = 4$ h
- Similar to reference approach at $\tau = 2$ h for large changes in surface changes
- But differences remain for small changes



Comparison of models

Varying SST in reference-state approach



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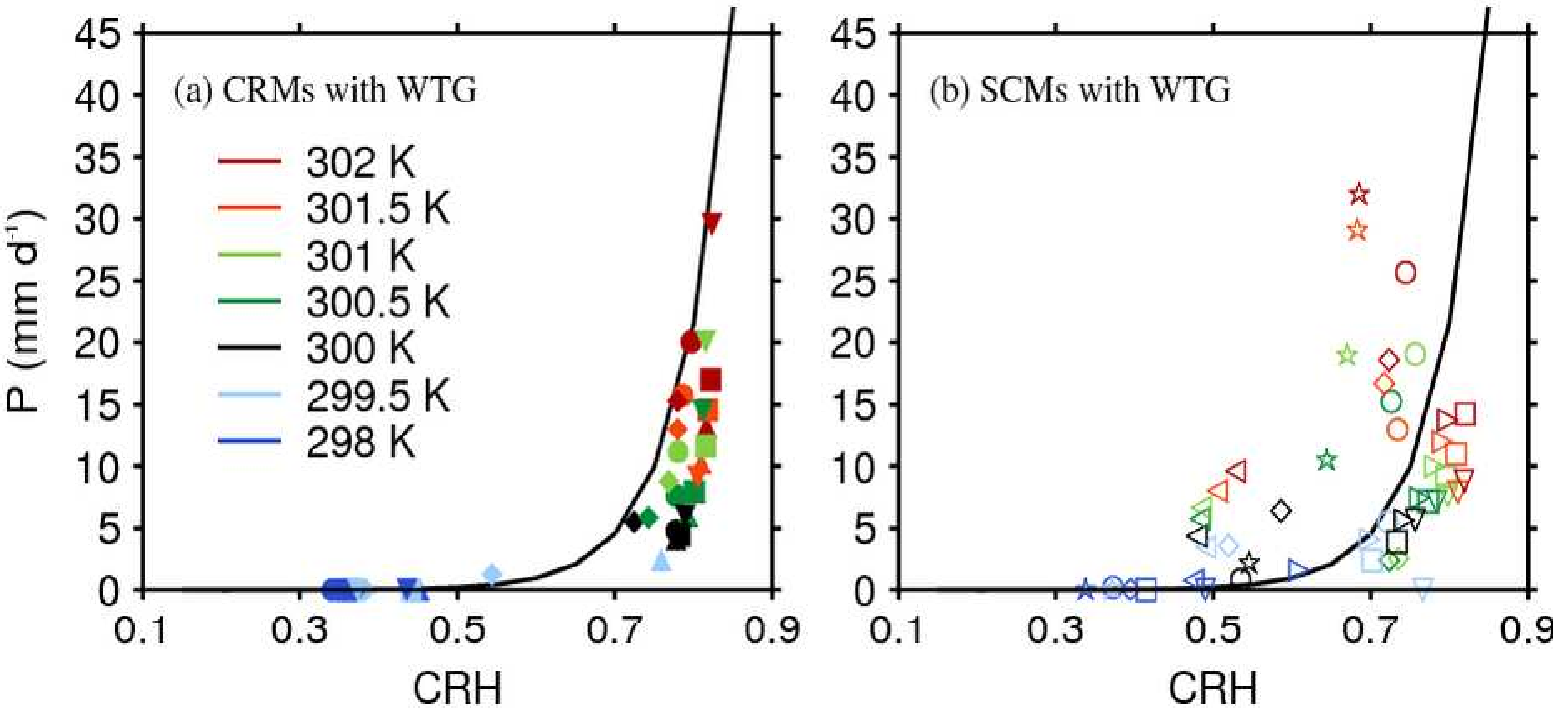
Precip and column relative humidity

Comparison with observational fit from satellite data over tropical oceans



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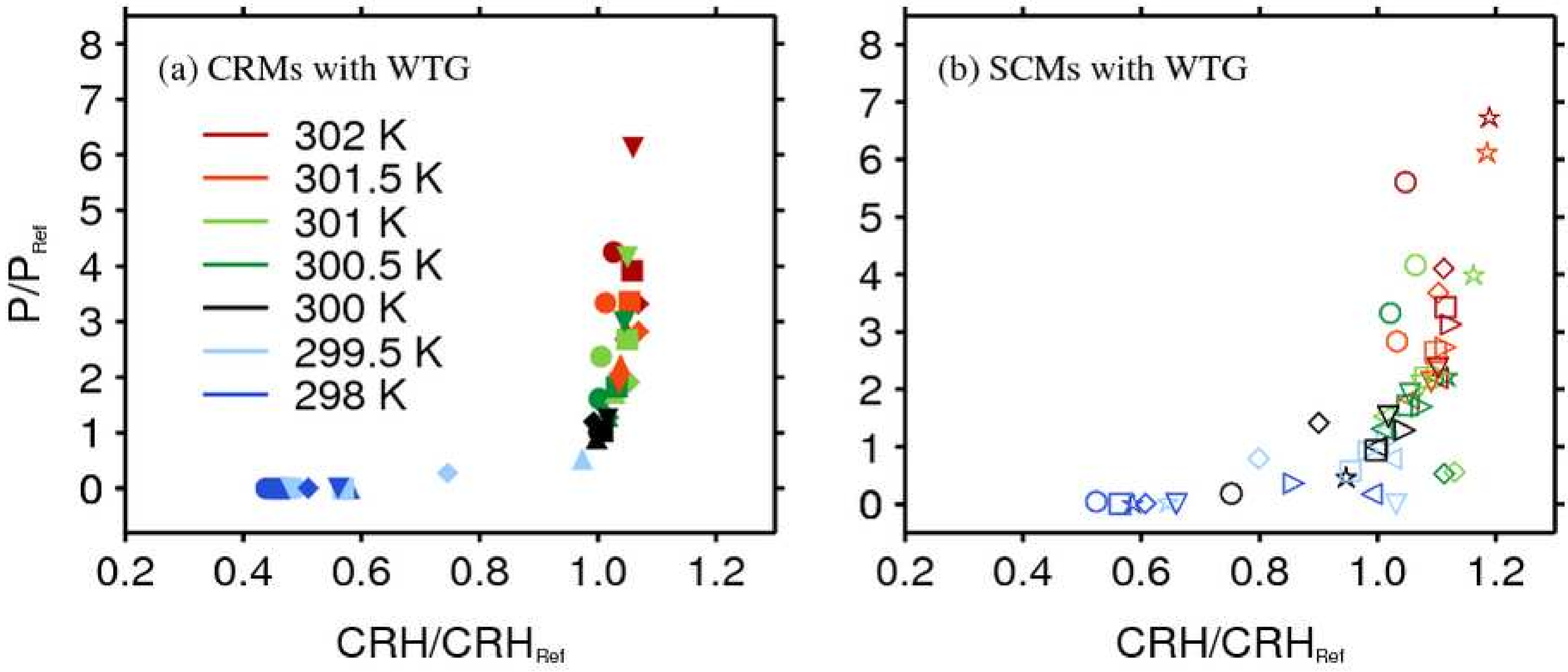
Precip and column relative humidity

Some collapse if scaled by reference RCE values



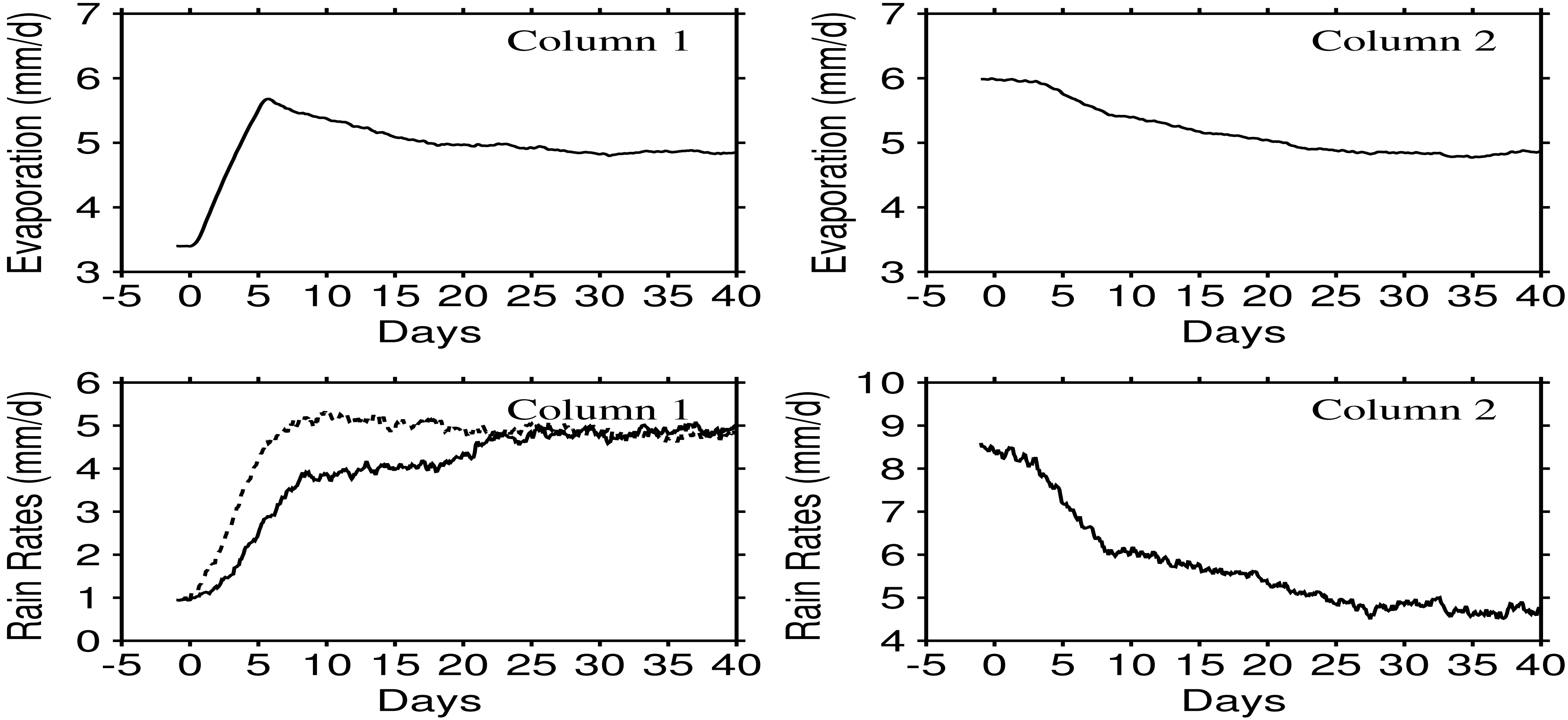
Transitional cases and parameterization testing

Transition, suppressed $\longrightarrow$ active

- Start from equilibrium state of two-region configuration with SST difference of 2K
- Rain rates are 0.98 and 8.47 mm/d in cold and warm regions
- Now transition to state of equal SST, no circulation, by
  1. local transition: increase cold SST by 2K
  2. remote transition: decrease warm SST by 2K
  3. mixed transition: increase cold and decrease warm SST by 1K

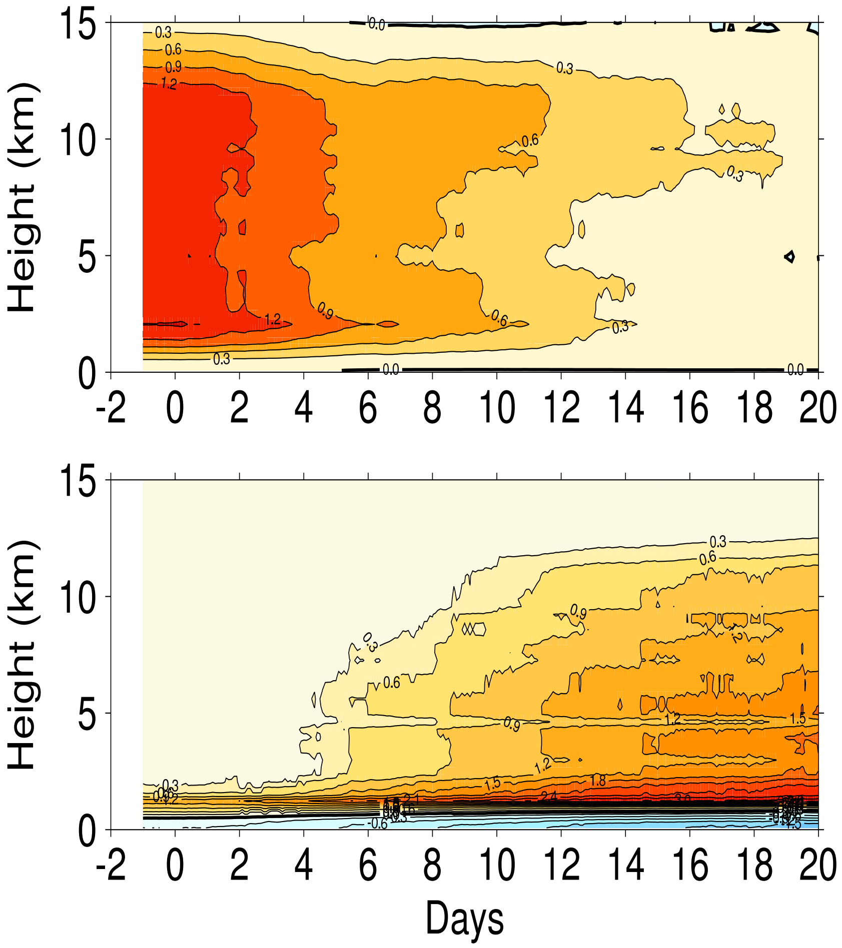
Local transition

The need to remove the WTG circulation slows the transition



Dashed line, set circulation to zero at transition time

Remote transition

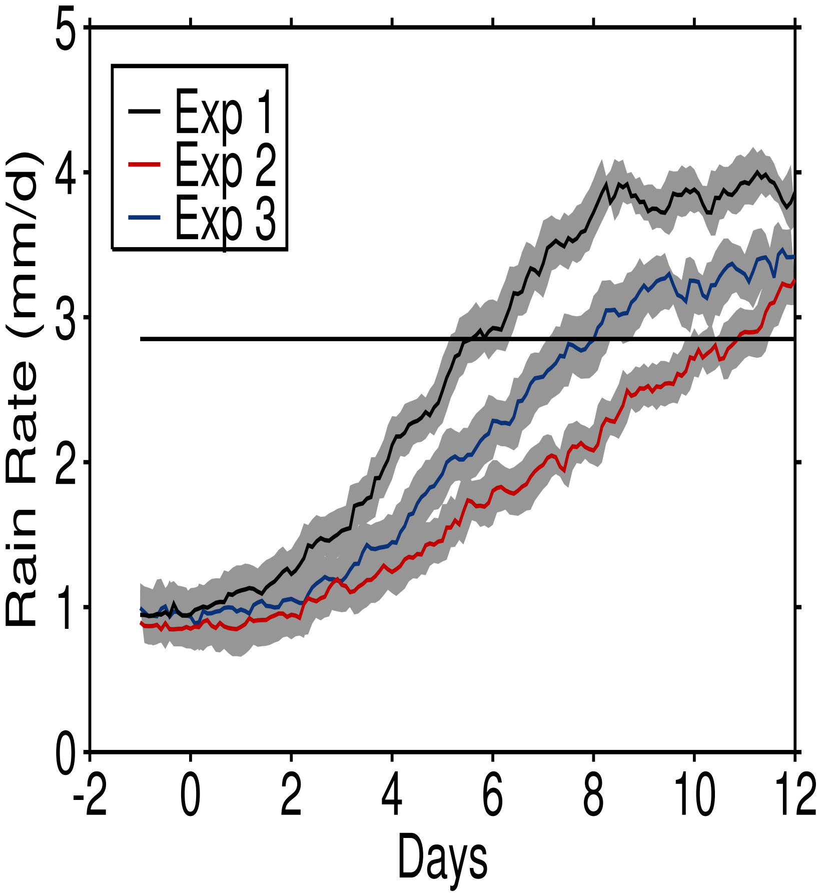


- Reduce evaporation in active region
- Leads to reduced convection there
- Reduces circulation
- Ultimately enough to allow convection in suppressed region

Transition times

Type	Time
Local	5.4 days
Remote	10.9 days
Mixed	8.7 days

Transition time: that required for rain rate to increase by half the amount needed to reach new equilibrium



Comparison with SCM

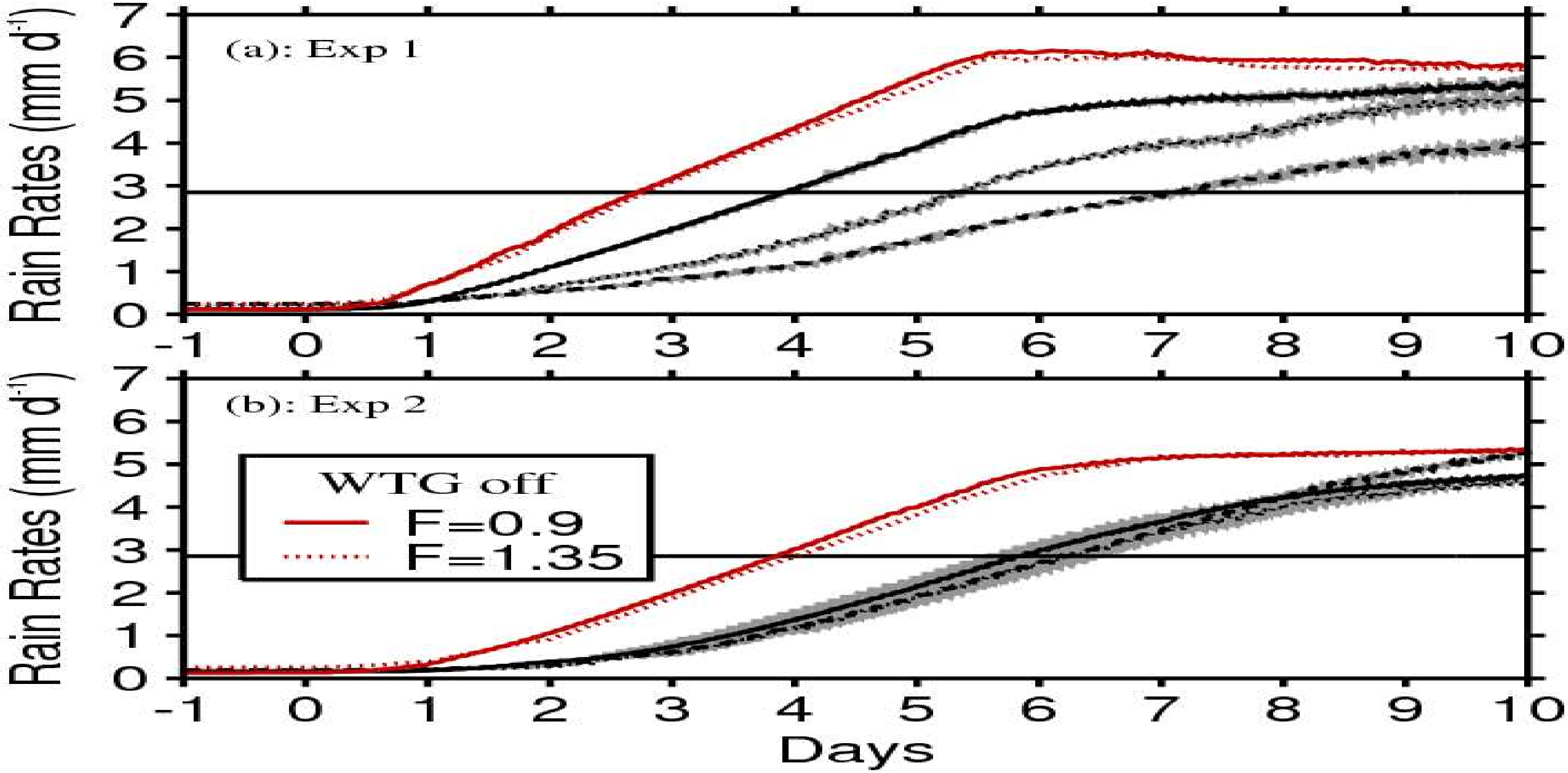
Type	CRM	SCM
Local	5.4	3.9
Remote	10.9	5.9
Mixed	8.7	4.8

- Repeat same transition experiments with the UM SCM (v7.8)
- All of the transitions are faster
- In the CRM, heating and moistening effects of large-scale circulation are about equally divided
- In the SCM, heating effects more important than moistening

Simple parameterization tests

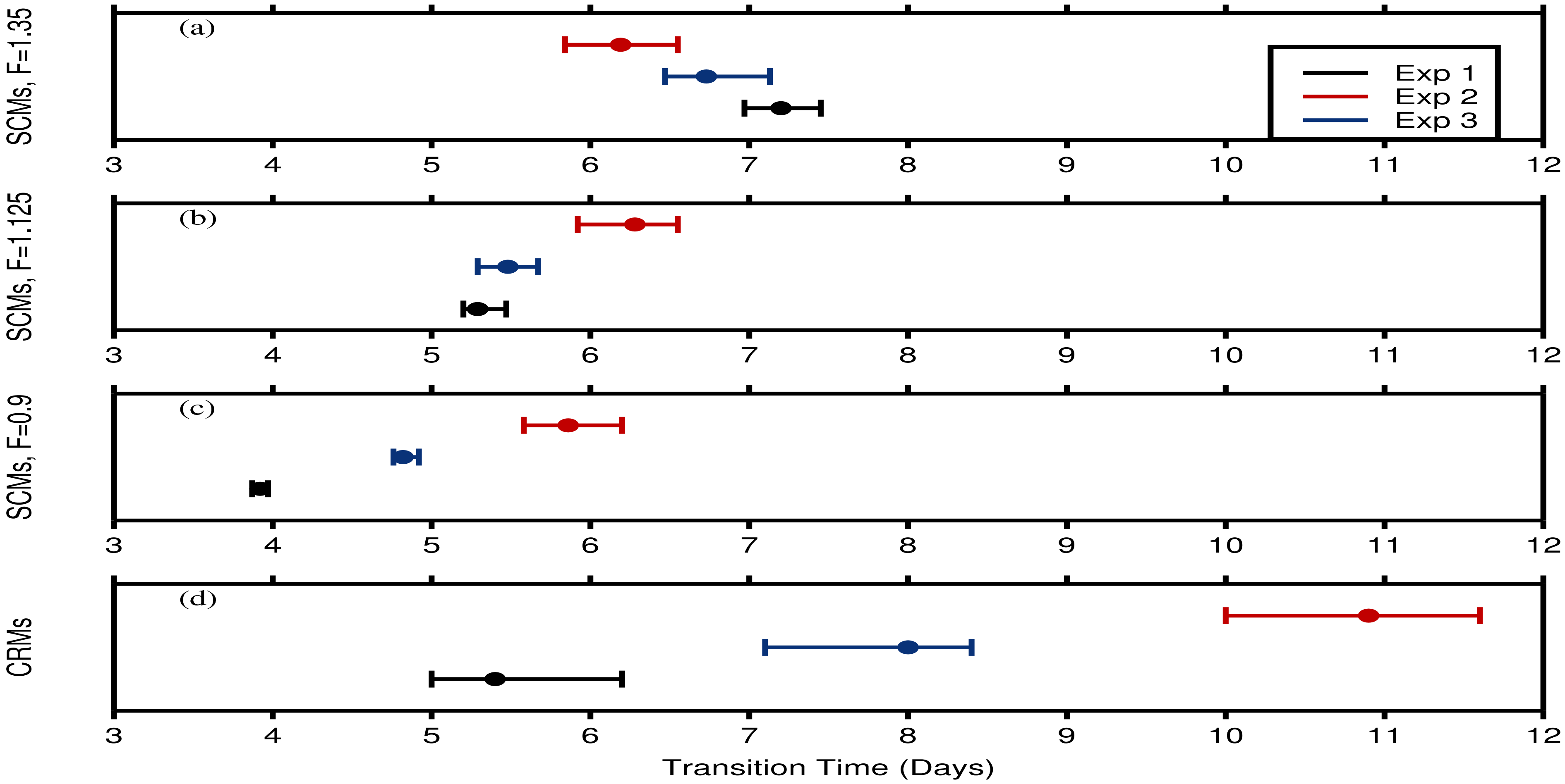
- Vary closure timescale of UM convection parameterization
  - very little effect: only alters high-frequency variability
- Vary entrainment and detrainment rates of UM convection parameterization
  - This is a key source of uncertainty in GCMs for both mean state and some modes of variability
  - We increase the entrainment and detrainment rates by 25% and 50%

Changes to entrainment



Feedback effects of entrainment rate on large-scale circulation do matter, rather than any more direct effect

Effects on Transition Times



- A non-trivial test of parameterization interactions with large-scale circulations.

Summary

- WTG approach allows coupling between convection and large-scale tropical circulations
- Normally coupling is to a reference RCE state and system is open
- This can produce ascent/descent/no circulation for uniform SST depending on the convection model
  - Caution: this does not happen in a closed two-region approach for any ε
- And can have multiple equilibrium with a non-precipitating state
  - Caution: this is very sensitive to the rather arbitrary treatment of the boundary layer circulation

Summary

- For distinct surface conditions, can produce good precip vs w_{LS} and precip vs CRH relationships
- CRH relation under WTG may provide a good test for SCM parameterizations
- The two region approach allows simulation of new idealized problems: e.g., effects of remote changes on suppressed $\longrightarrow$ active transitions
- Transitions under WTG may provide a difficult test for SCM parameterizations

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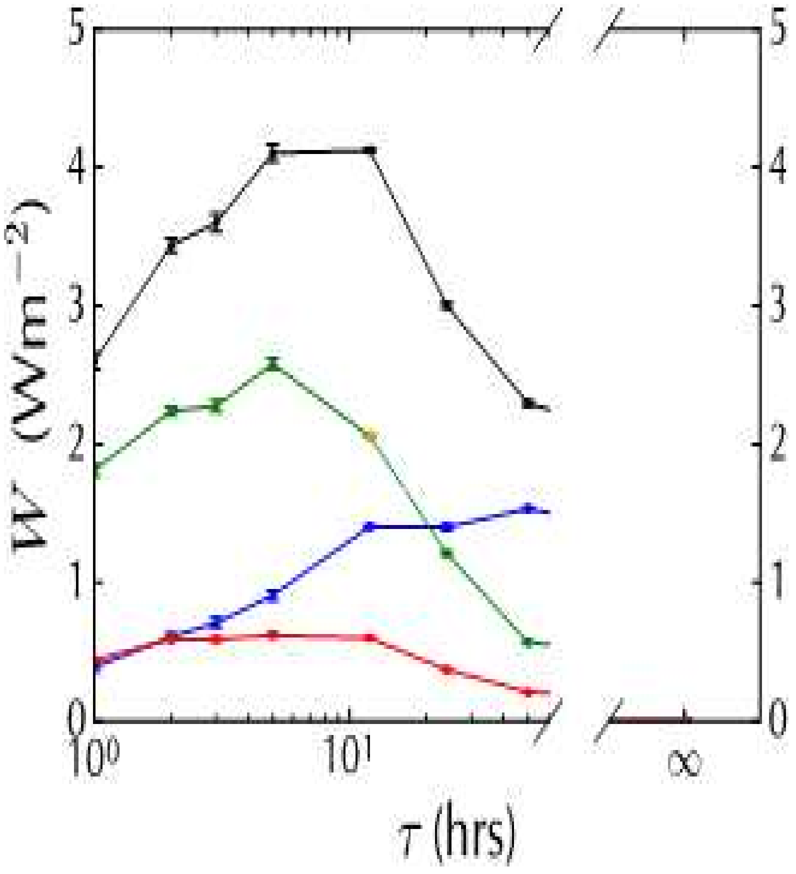
Thermodynamic Analysis

$$\oint T dS \approx \oint B dz$$

$$+g \oint r_T dz$$

$$-\sum_{w=v,l,i} \oint G_w dr_w$$



With Kamieniecki, Ambaum