Feedbacks between moisture, cumulus convection and large-scale circulations over the tropical oceans

Christopher S. Bretherton
Departments of Atmospheric Science and Applied Mathematics
University of Washington

…with help from Peter Blossey, Marat Khairoutdinov, and others

What makes tropical dynamics unique?

Moist convection!

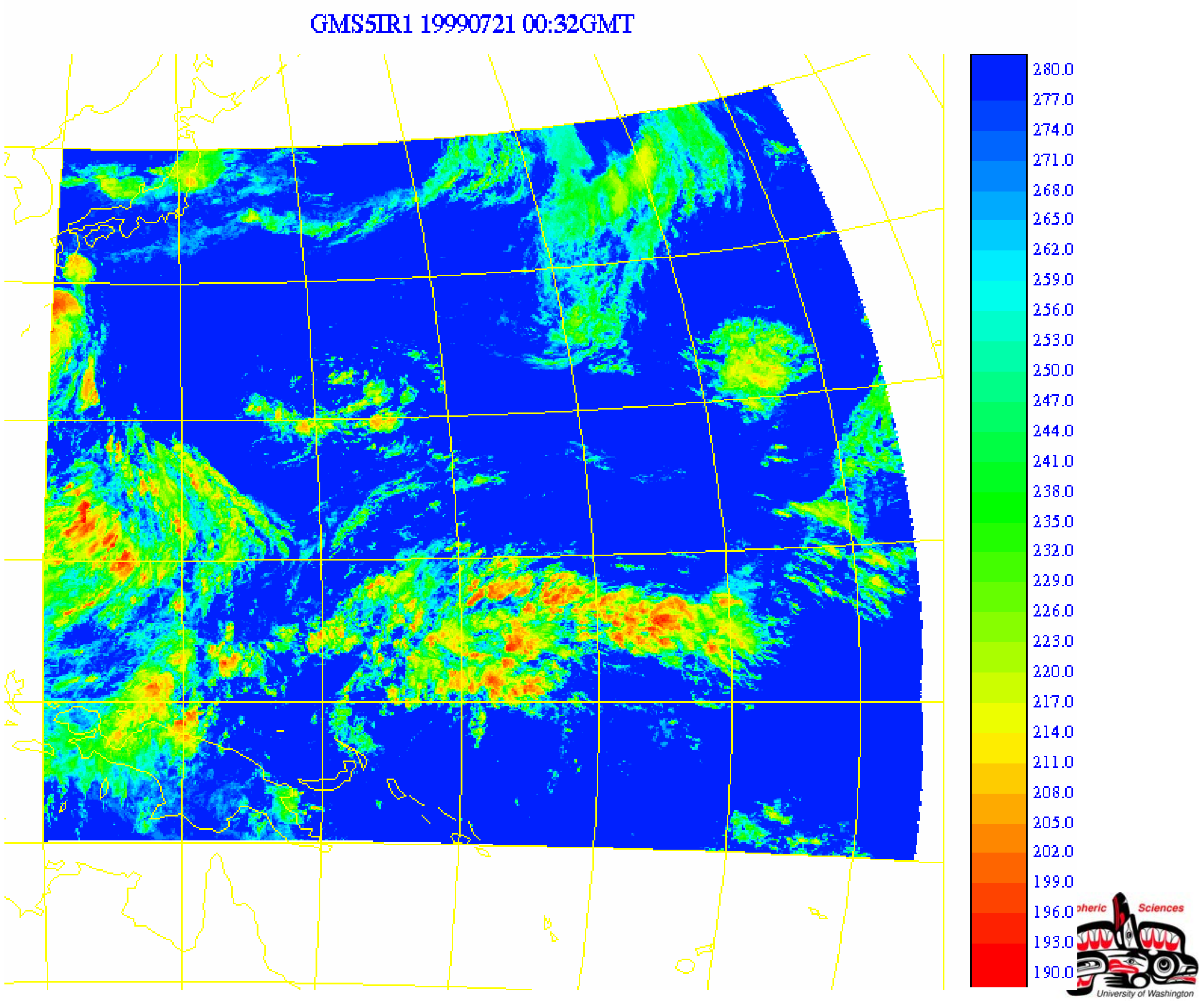
- Heat engine of large-scale circulations (rainfall) .
- Determines tropical thermal stratification.
- Tightly connected to water vapor, clouds, radiation.
- Scale interaction
- Strong 2-way link to SST and land surface properties.

This talk

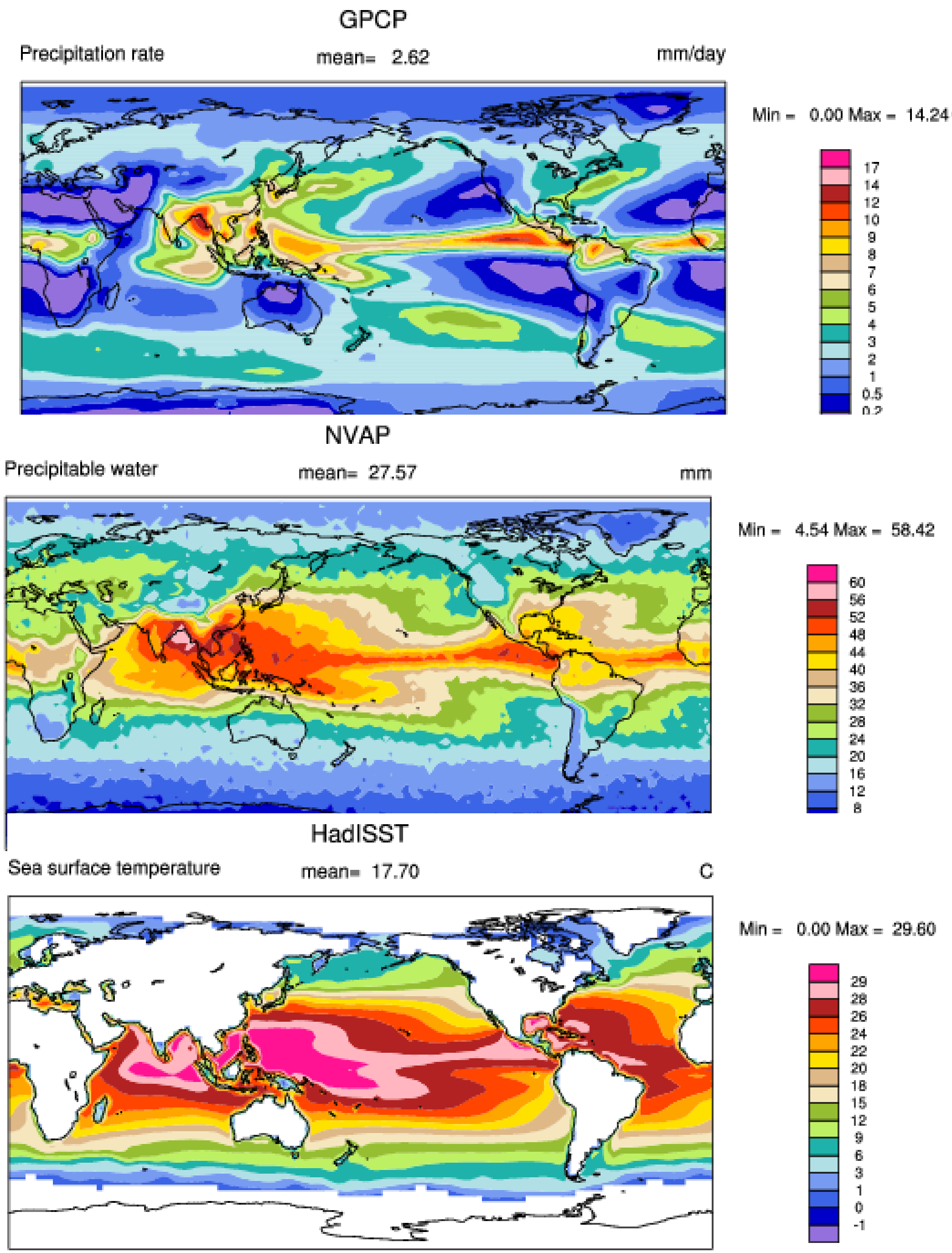
Role of feedbacks between convection and water vapor in organizing large-scale tropical circulations in a CRM.

- Convective self-aggregation over uniform SST
- Mock-Walker circulation

Atmospheric Sciences
University of Washington

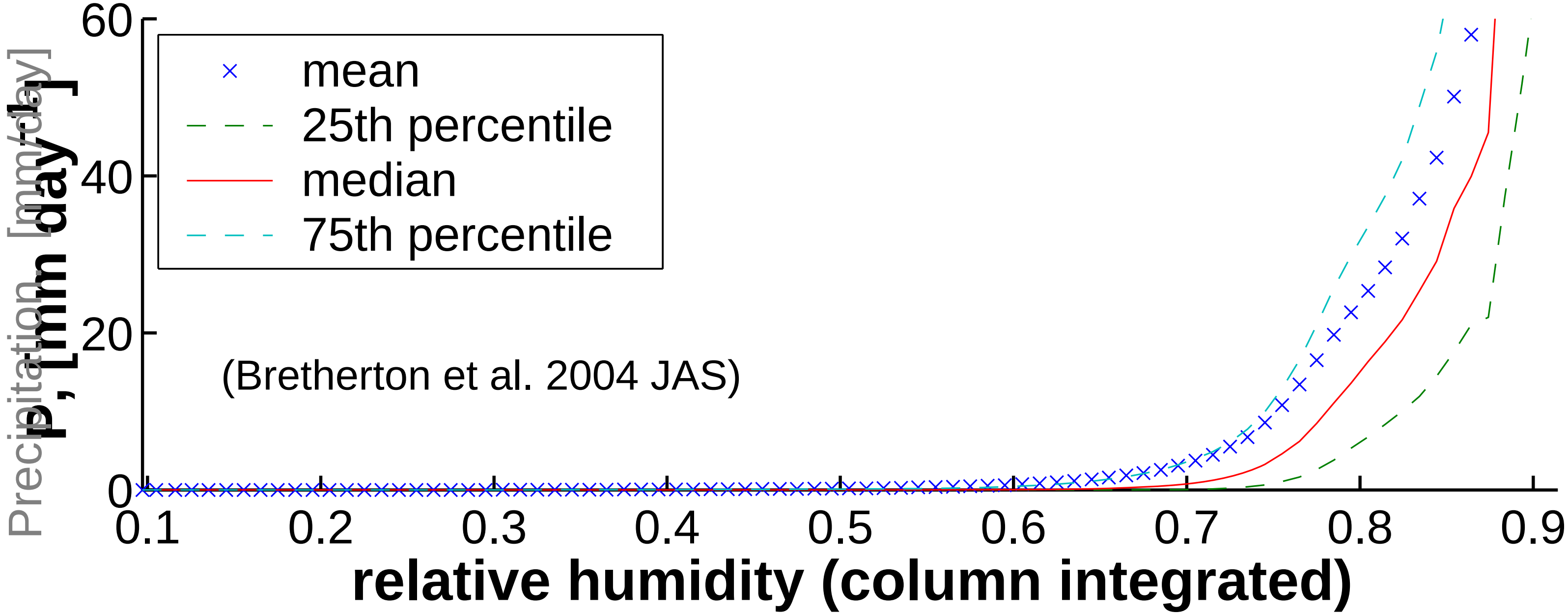

GMS5IR1 19990721 00:32GMT
280.0
277.0
274.0
271.0
268.0
265.0
262.0
259.0
256.0
253.0
250.0
247.0
244.0
241.0
238.0
235.0
232.0
229.0
226.0
223.0
220.0
217.0
214.0
211.0
208.0
205.0
202.0
199.0
196.0
193.0
190.0
University of Washington

Mean rainfall-humidity correlations (JJA mean)



Atmospheric Sciences
University of Washington

Strong SSM/I observed rainfall-humidity correlation on daily timescales as well



Radiative-Convective Equilibrium

A traditional 1D perspective on the atmospheric structure of the deep tropics and its response to climate forcings (e. g. Manabe and Strickler 1964).

- Uniform insolation.
- No ambient rotation.
- Uniform surface (e. g. constant SST or zero-flux).

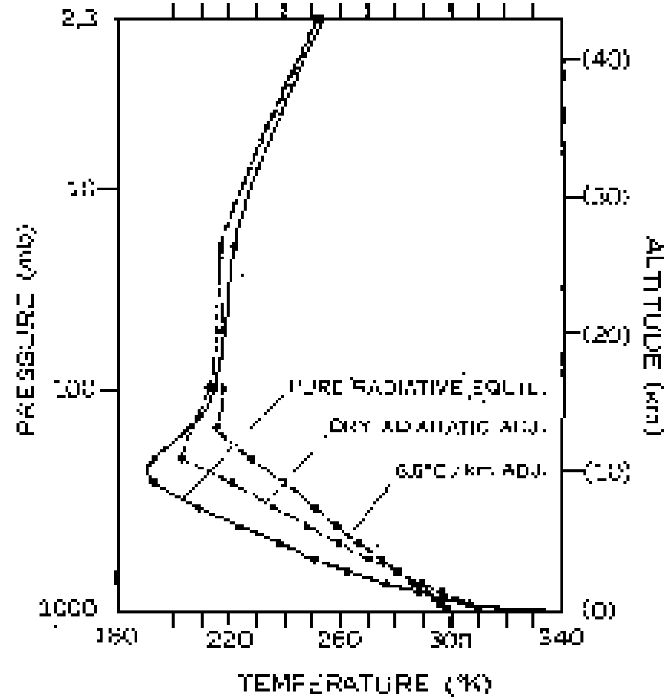
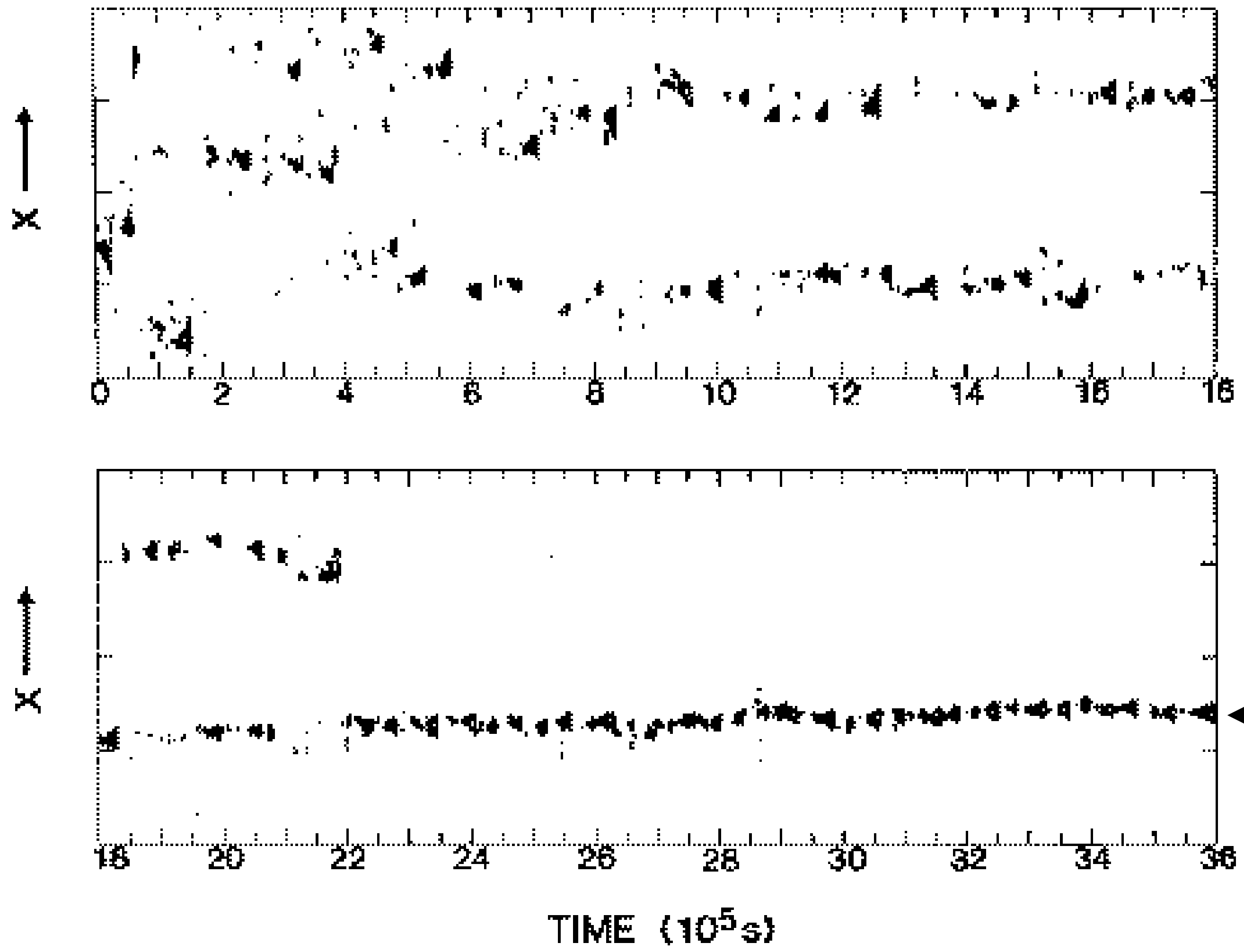


FIG. 4. The dashed, dotted, and solid lines show the thermal equilibrium with a critical lapse rate of 6.5 deg km^{-1}, a dry-adiabatic critical lapse rate (10 deg km^{-1}), and pure radiative equilibrium.

2D domain RCE simulation

(Held et al. 1993, A = 640 km, Δx = 5 km, zero mean wind)



single stationary updraft

FIG. 4. Precipitation as a function of time and x in the case in which the mean wind is constrained to vanish.

(Held et al. 1993)

Imposed weak 1 m s^{-1} km^{-1} mean vertical shear over lowest 5 km destroys organization by shearing out moist anomaly.

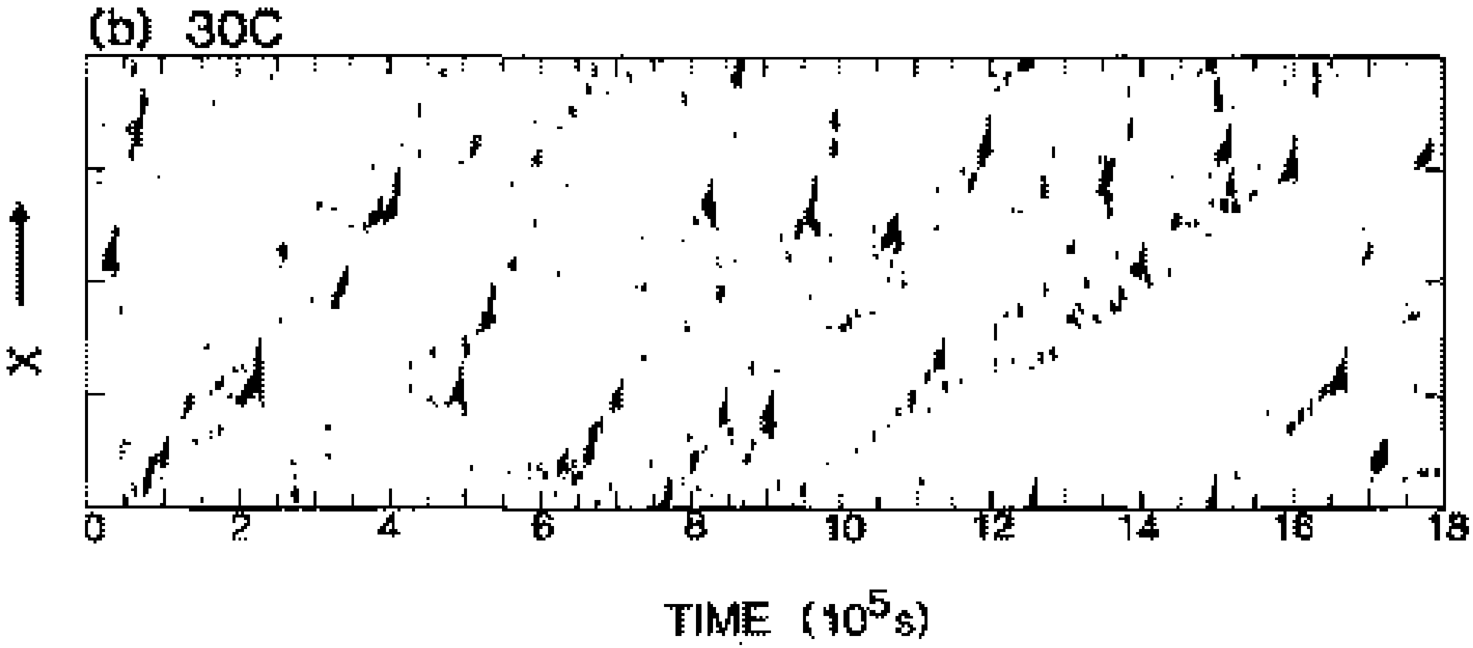
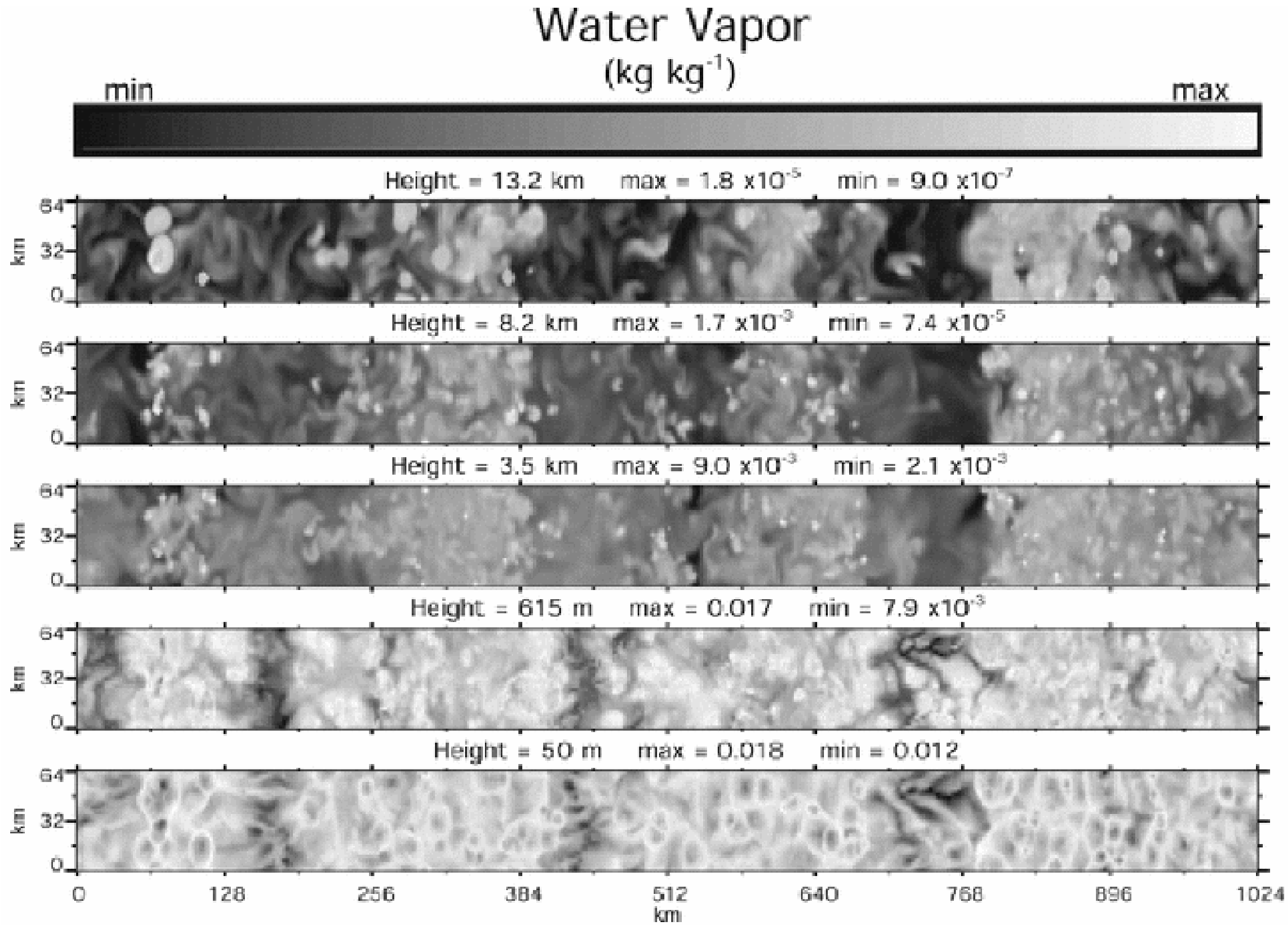


FIG. 7. Precipitation as a function of time and x in the case with a prescribed mean shear (a) 25°C and (b) 30°C.

"We are convinced that it is the moisture field, rather than the large-scale low-level convergence pattern, that gives the 'wet spot' its memory". (Held et al. 1993)

Tompkins (2001, JAS)

- 1024x64 km domain, Δx = 2 km. Specified radiation, interactive surface fluxes. Convective feedback on mean shear was enabled, but mean winds did not build up. Self-aggregation in O(10 days).



(Day 15)

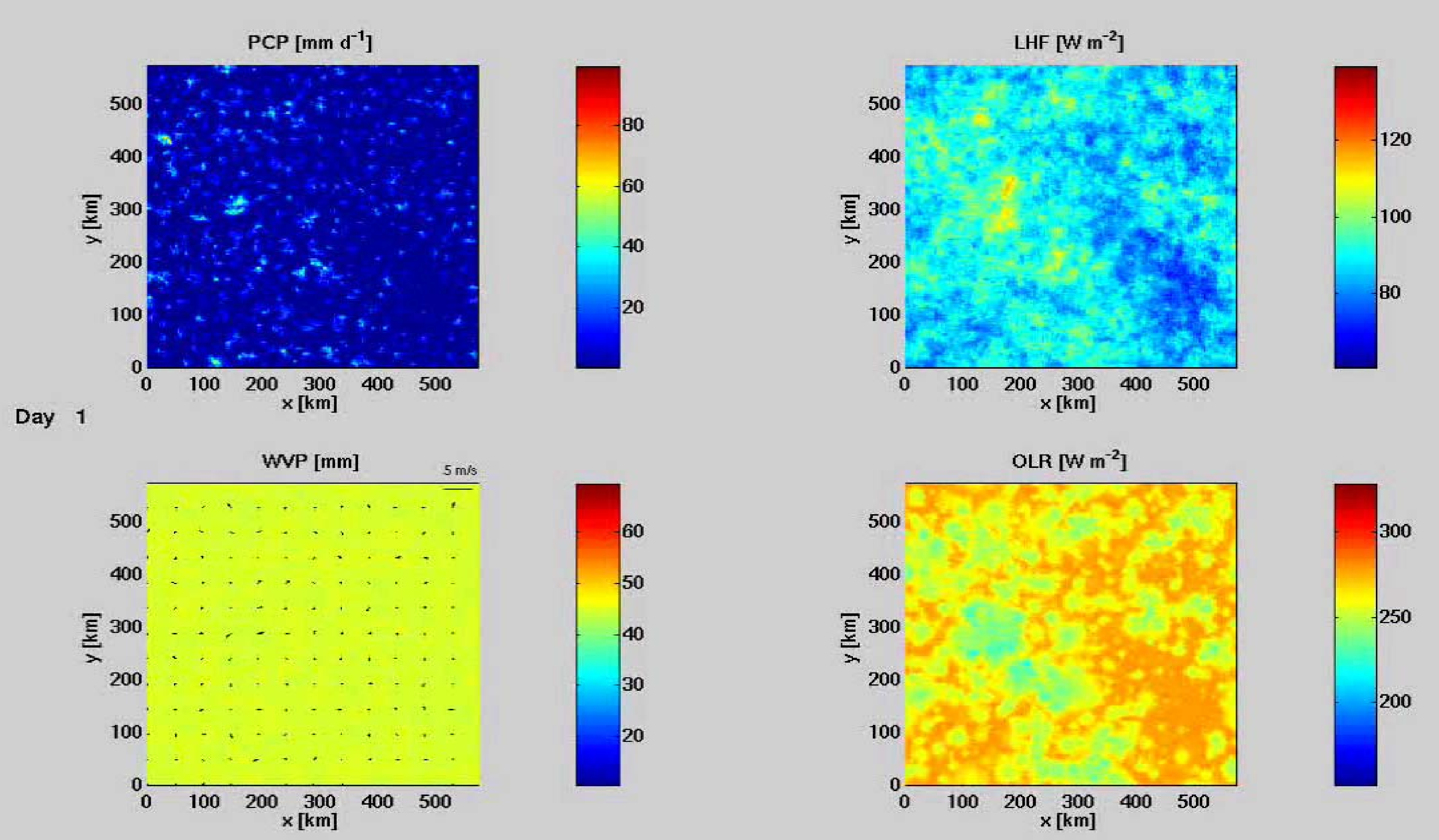
Self-aggregation over 576x576 km domain

(Bretherton et al. 2005 JAS)

Spatially uniform RCE over constant SST appears to be unstable to ‘self-aggregation instability’ on quasi-2D domains. Also on fully 3D domain? Theoretical model?

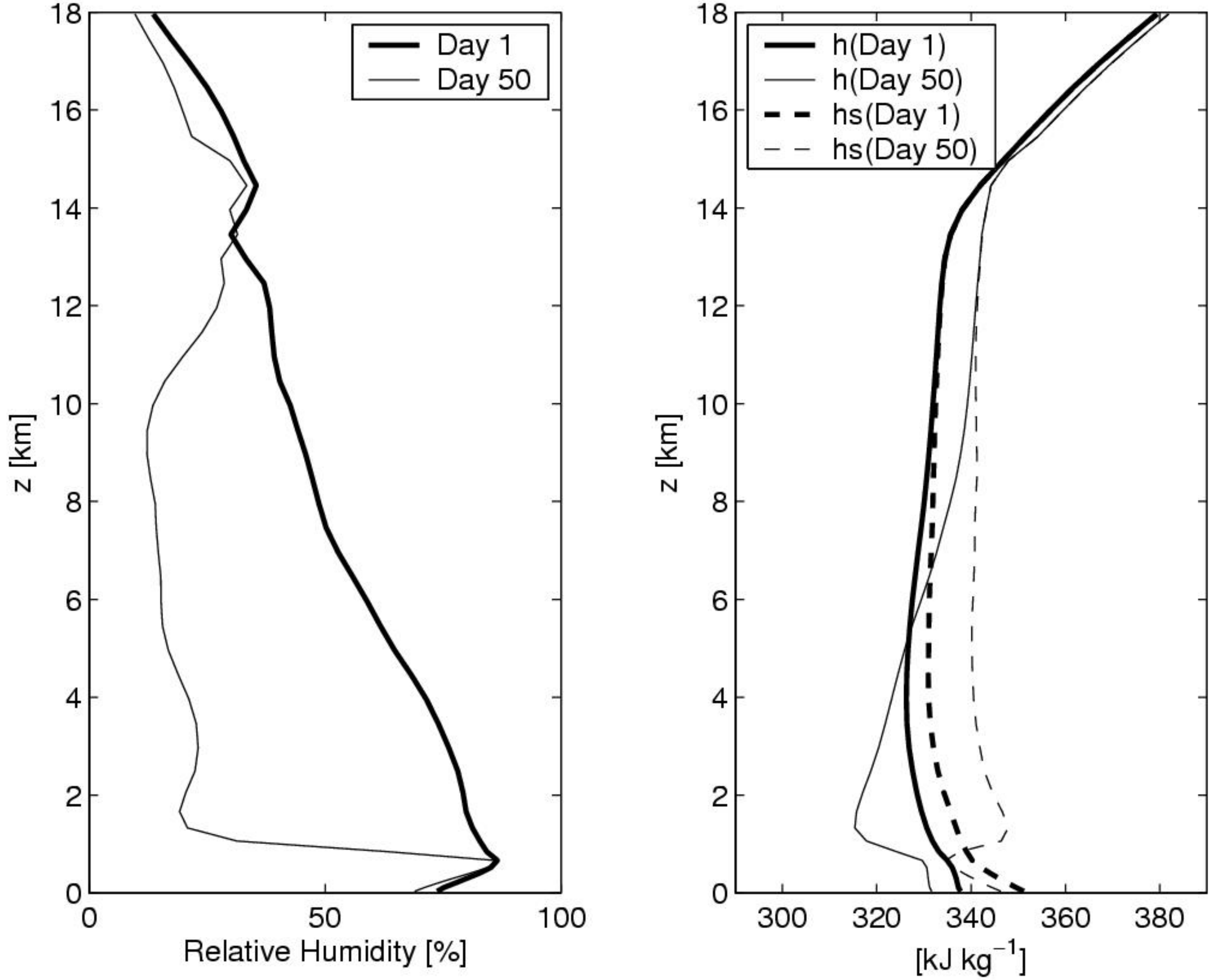
- SAM6.1 CRM (Khairoutdinov and Randall 1993)
- Doubly periodic, Δx = 3 km, 64 vertical levels
- No initial mean wind, CMT affects mean flow.
- Interactive surface fluxes and radiation.
- First run ‘small-domain’ 96x96 km 301 K RCE simulation to steady state (popcorn convection, no aggregation).
- Tile onto the large domain, add random perturbations, integrate 100 days.

100 days of self-aggregation



Atmospheric Sciences
University of Washington

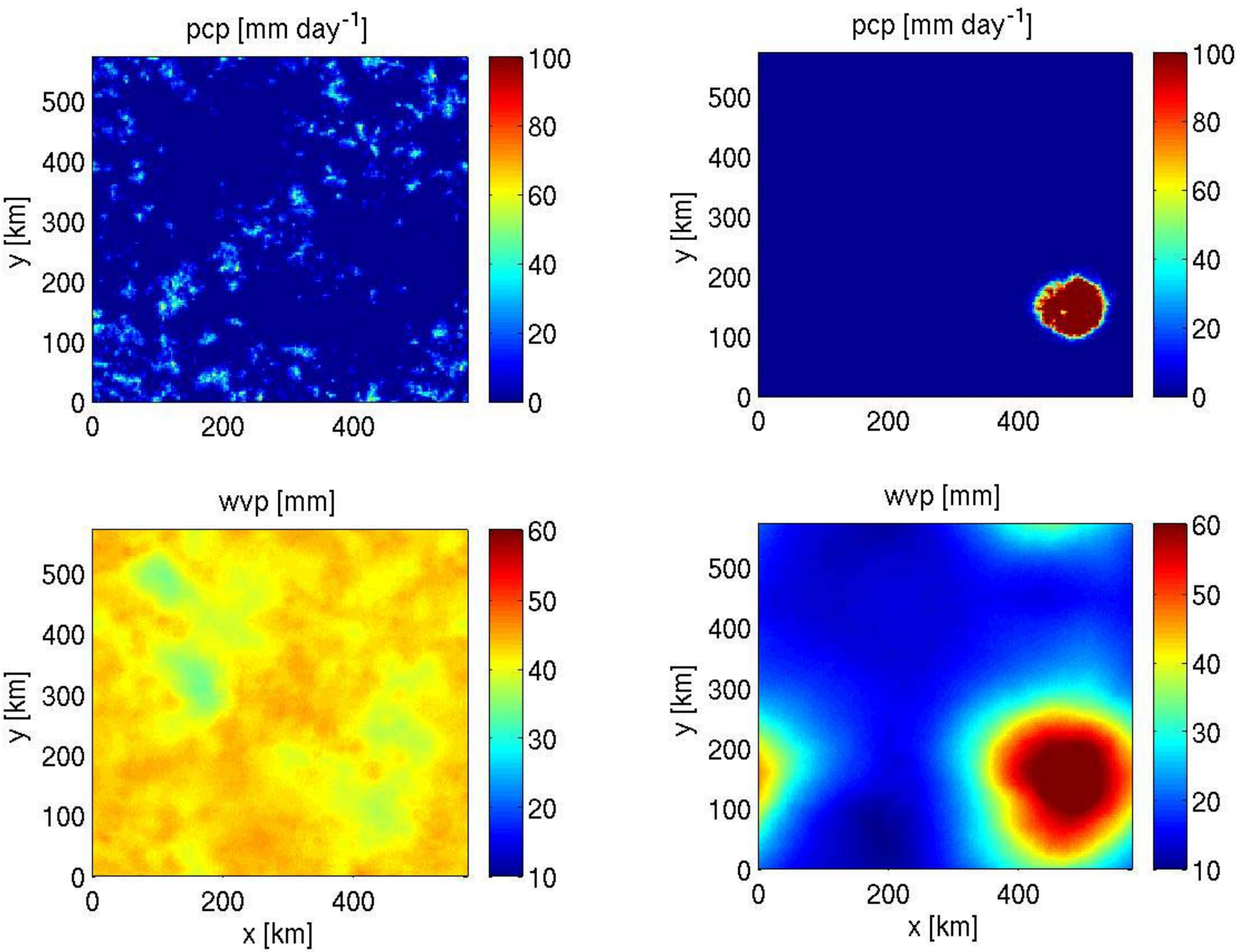
Mean sounding profoundly dries and warms



…so how does self-aggregation ‘instability’ happen?

Day 6 avg.
incipient self-aggregation

Day 50 avg.
One convective center



Moist static energy budget analysis of self-aggregation

- Use daily horiz. averages over 72x72 km subdomains (space-time averaging on sub-aggregation scale)
- Use subdomain tropospheric column-integrated ‘<>’ budgets of moist static energy $h = c_p T + Lq + gz\ [- L_f q_i]$ to understand self-aggregation feedbacks.

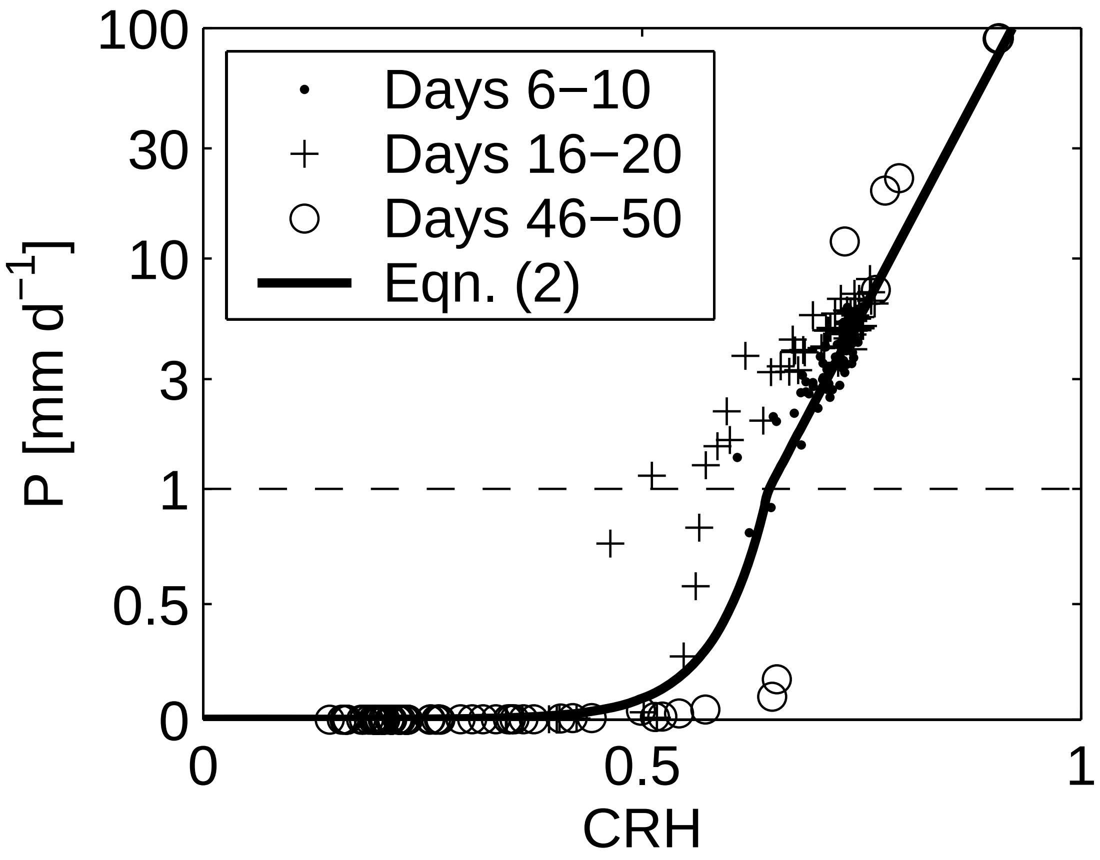
$$
\begin{array}{rcl}
d\langle s\rangle/dt & = & LP + SHF - \Delta R - \langle\nabla\cdot(\mathbf{u}s)\rangle \\
+\ d\langle Lq\rangle/dt & = & -LP + LHF \qquad\qquad - \langle\nabla\cdot(\mathbf{u}q)\rangle \\
\hline
d\langle h\rangle/dt & = & THF - \Delta R - \langle\nabla\cdot(\mathbf{u}h)\rangle
\end{array}
$$

<h> is used so we can moist convective rainfall (LP) as response to external forcing (so don’t want LP on RHS).

- Horizontal T variations (´) small, so $\langle h\rangle' \approx \langle Lq\rangle' = LW'$, where W is water vapor path.
- Self-aggregation if $d\langle h\rangle/dt$ positively correlated to $\langle h\rangle$, so moist regions get moister and dry regions get drier.

Moister blocks precipitate more

Define 'column relative humidity' $r = W/W_{sat}$. Then…



$P \approx P_{RCE} \exp(a_m[r - r_{RCE}])$,
$P_{RCE} = 3.5$ mm d^{-1},
$a_m = 16.6$,
$r_{RCE} = 0.72$.

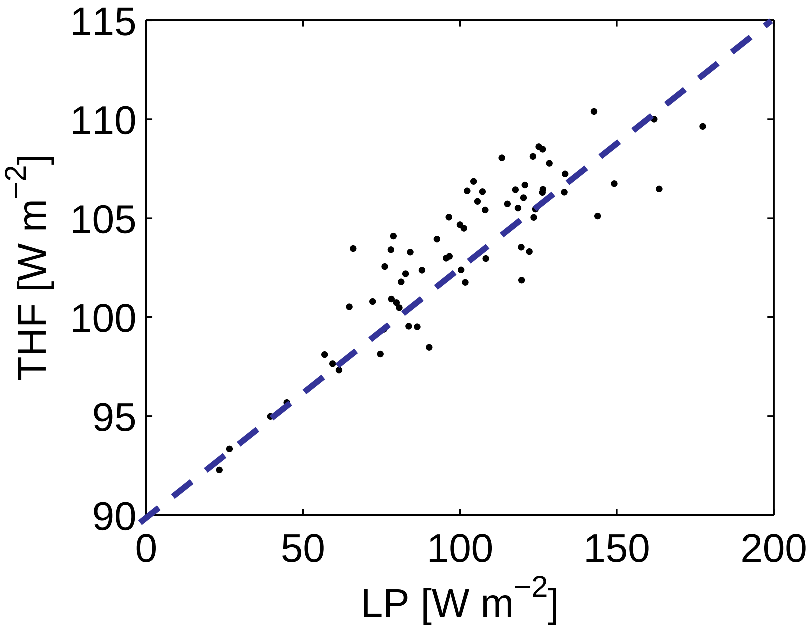
(Bretherton et al. 2005)

(Relationship depends slightly on evolving T profile)

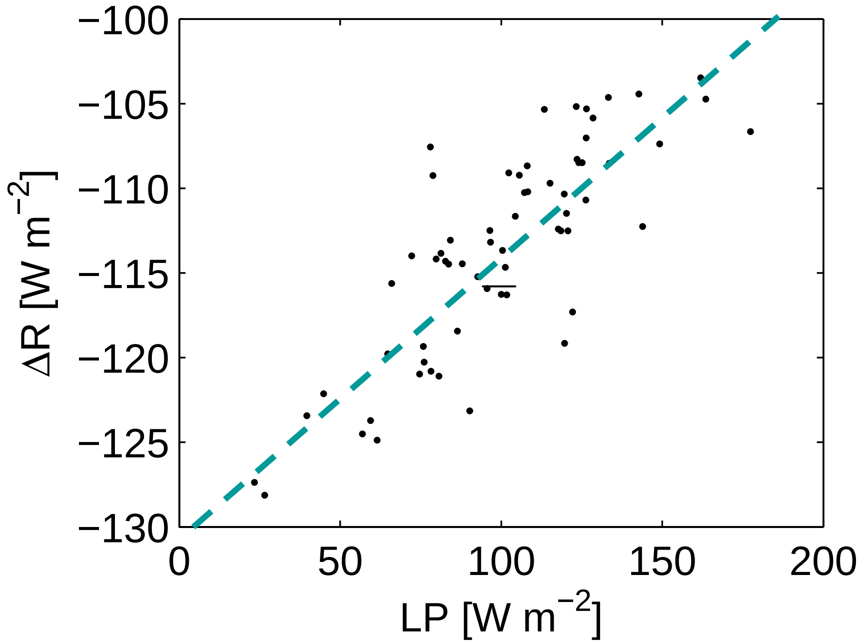
…similar relationship observed over tropical oceans on daily timescales (Bretherton et al. 2004)

Convection influences diabatic forcing

Gustiness (cold pools)



Anvil greenhouse

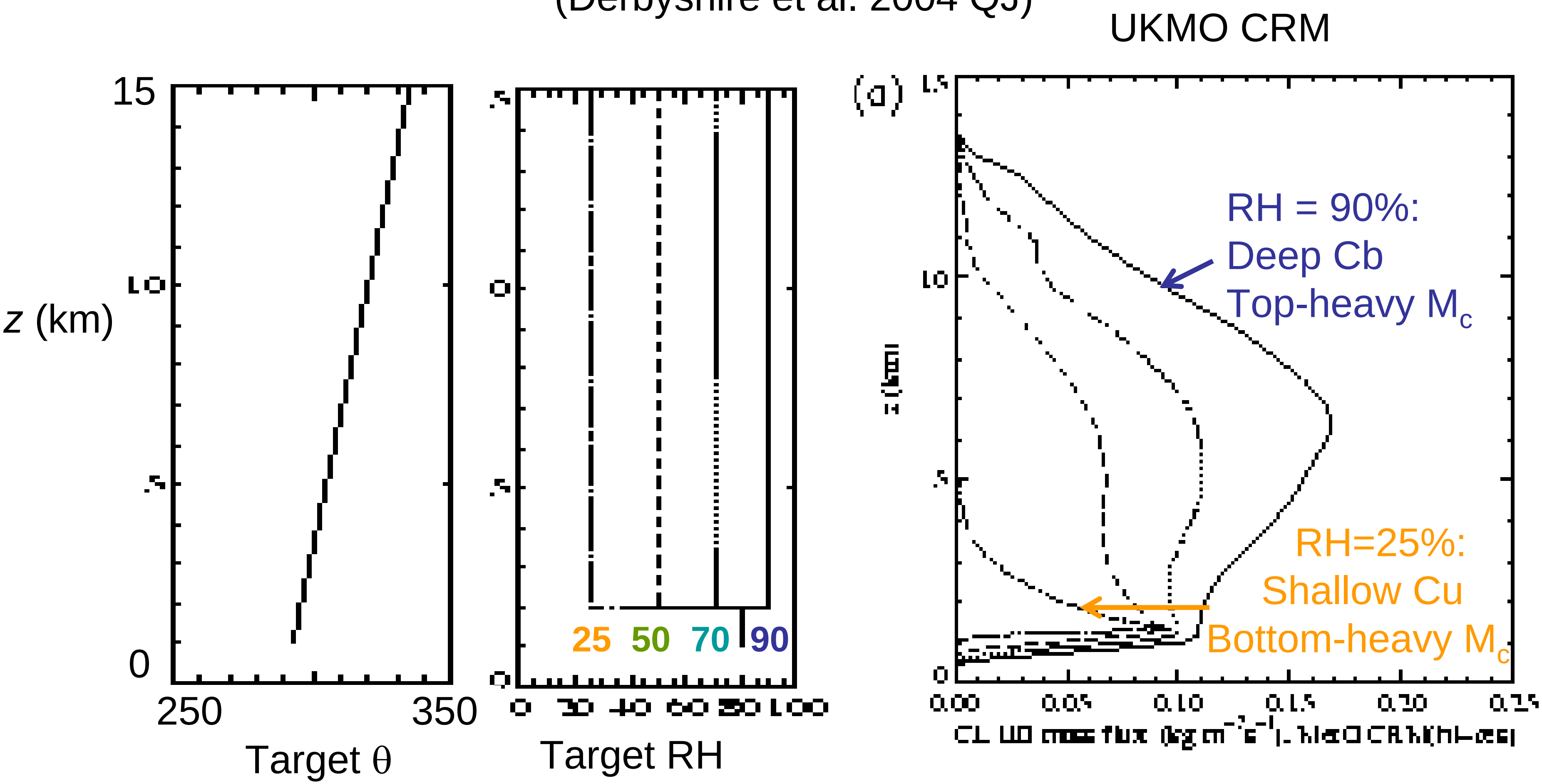


$dTHF/dLP = c_S = 0.12$

$d\Delta R/dLP = c_R = 0.17$

Cu depths sensitive to lower tropospheric moisture

(Derbyshire et al. 2004 QJ)

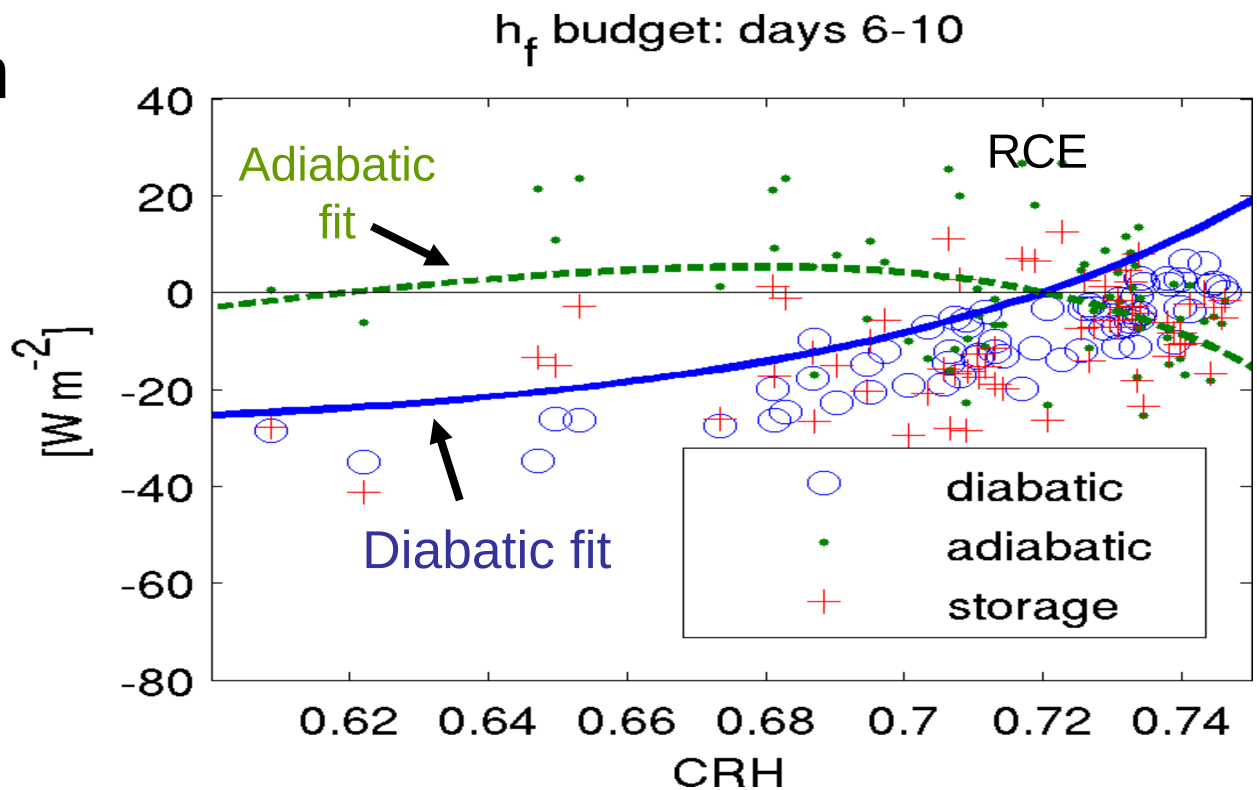


- Most cumuli entrain vigorously (1-2 km^{-1}).
- Entrainment of dry air evaporates Cu, steals their buoyancy.

⇒Deep Cb require moist environment as well as CAPE.

Atmospheric Sciences
University of Washington

Advection



ADVH = - <∇·(**u**h)> = $\alpha_h L(P - P_{RCE})(r_h - r)$, $\alpha_h = 1.8$, $r_h = 0.62$

…is stabilizing for r > 0.68.

A simple MSE-based theory of self-aggregation

$$d\langle h\rangle/dt = THF - \Delta R - \langle\nabla\cdot(\mathbf{u}h)\rangle$$

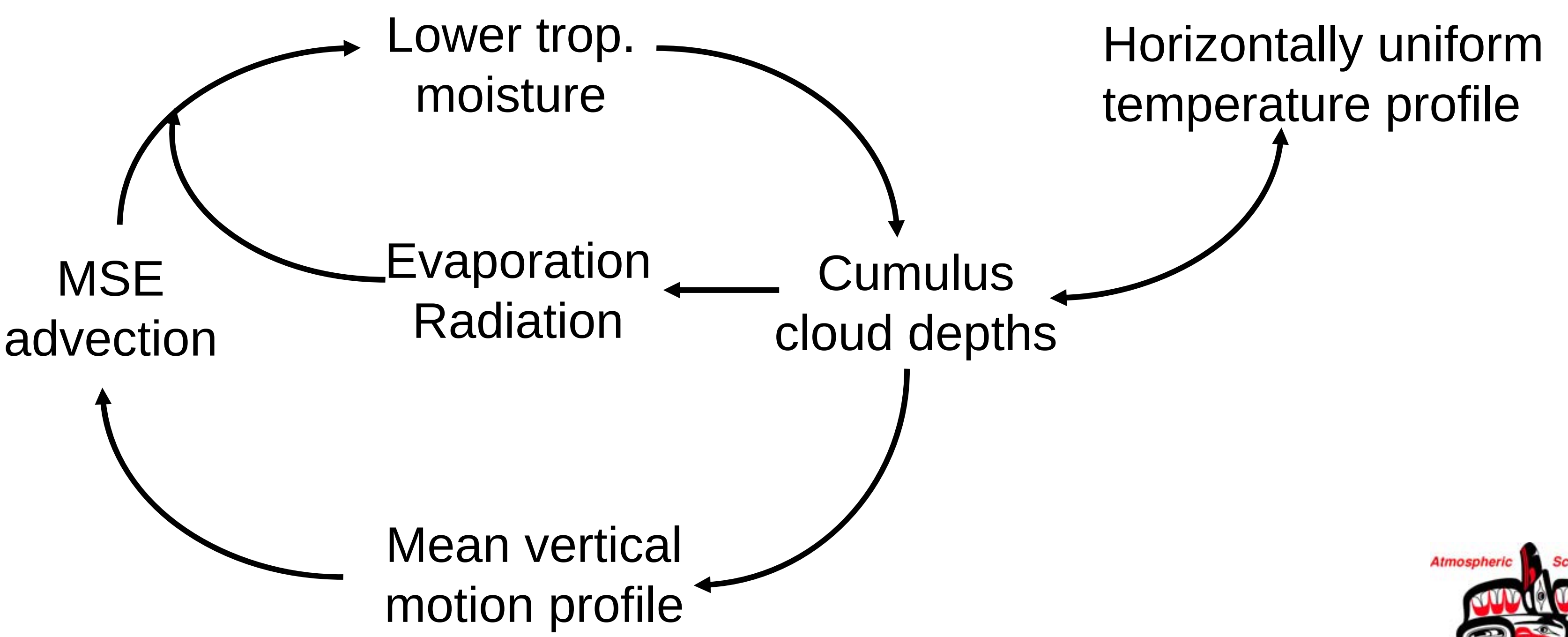
$$\Rightarrow \quad LW_{sat}\, dr/dt = (c_S + c_R)\, LP(r) + ADVH(r,P(r)) \; [+ Noise(t)]$$

…an ODE for the column moisture r.

Instability if RHS positively correlated with r near RCE:

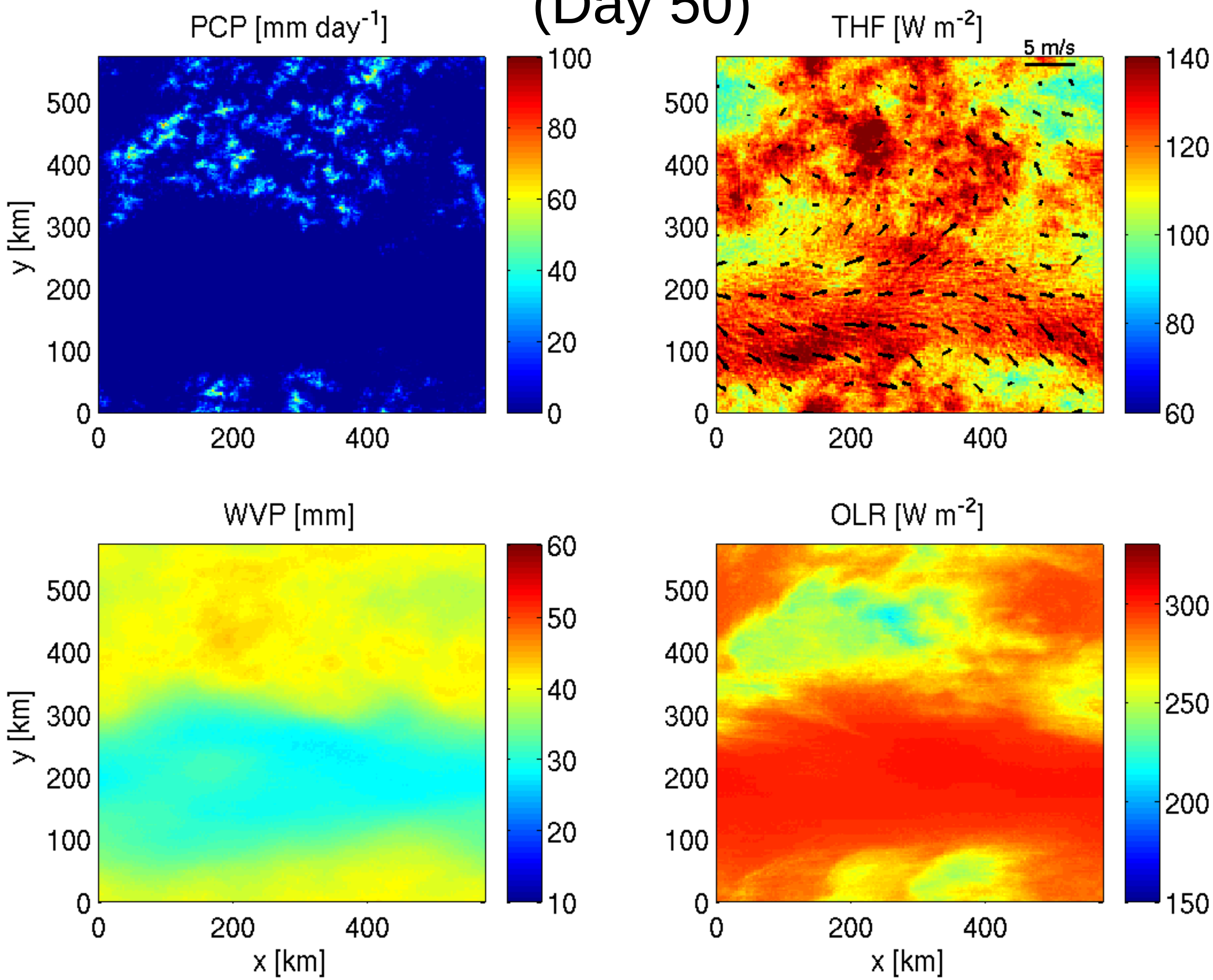
$$(c_S + c_R) + dADVH/dr|_{RCE} > 0$$

$$(0.12+0.17) \quad -0.18 \qquad = 0.11 \Rightarrow \text{ unstable (9d e-fold)}$$



Self-aggregation under unidirectional shear

(Day 50)

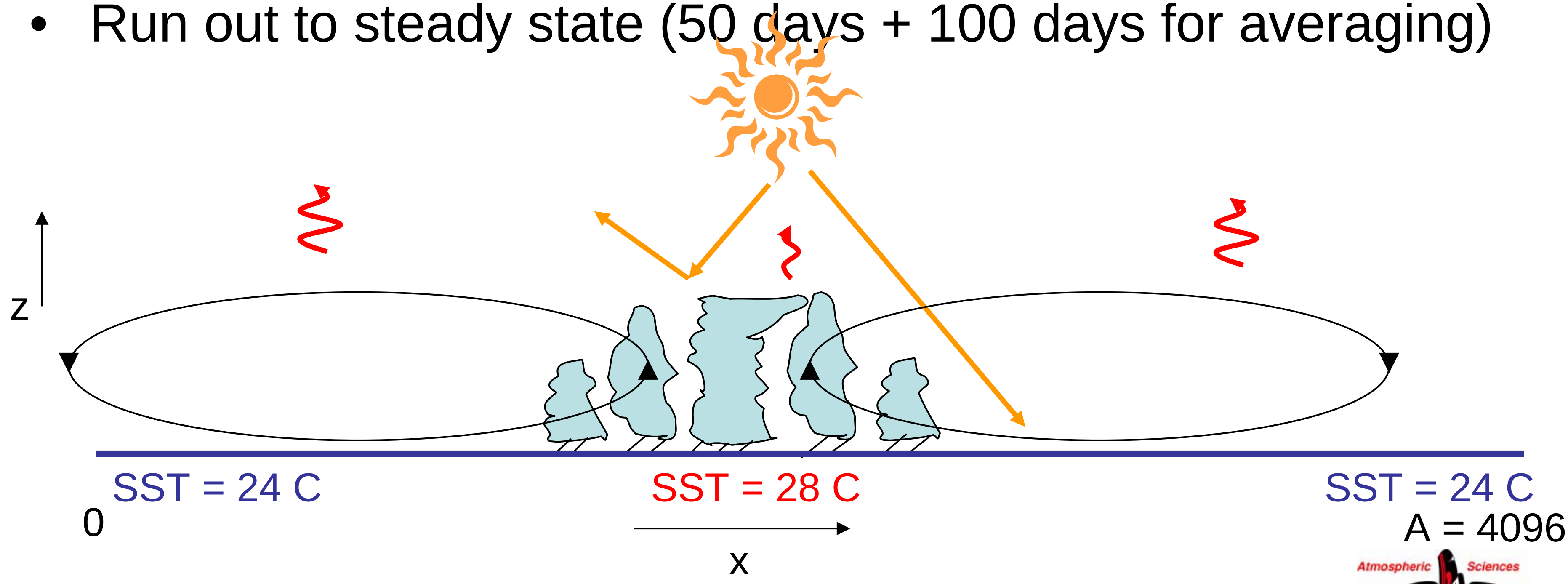


Fixed-SST Mock-Walker circulation (Grabowski et al. 2000)

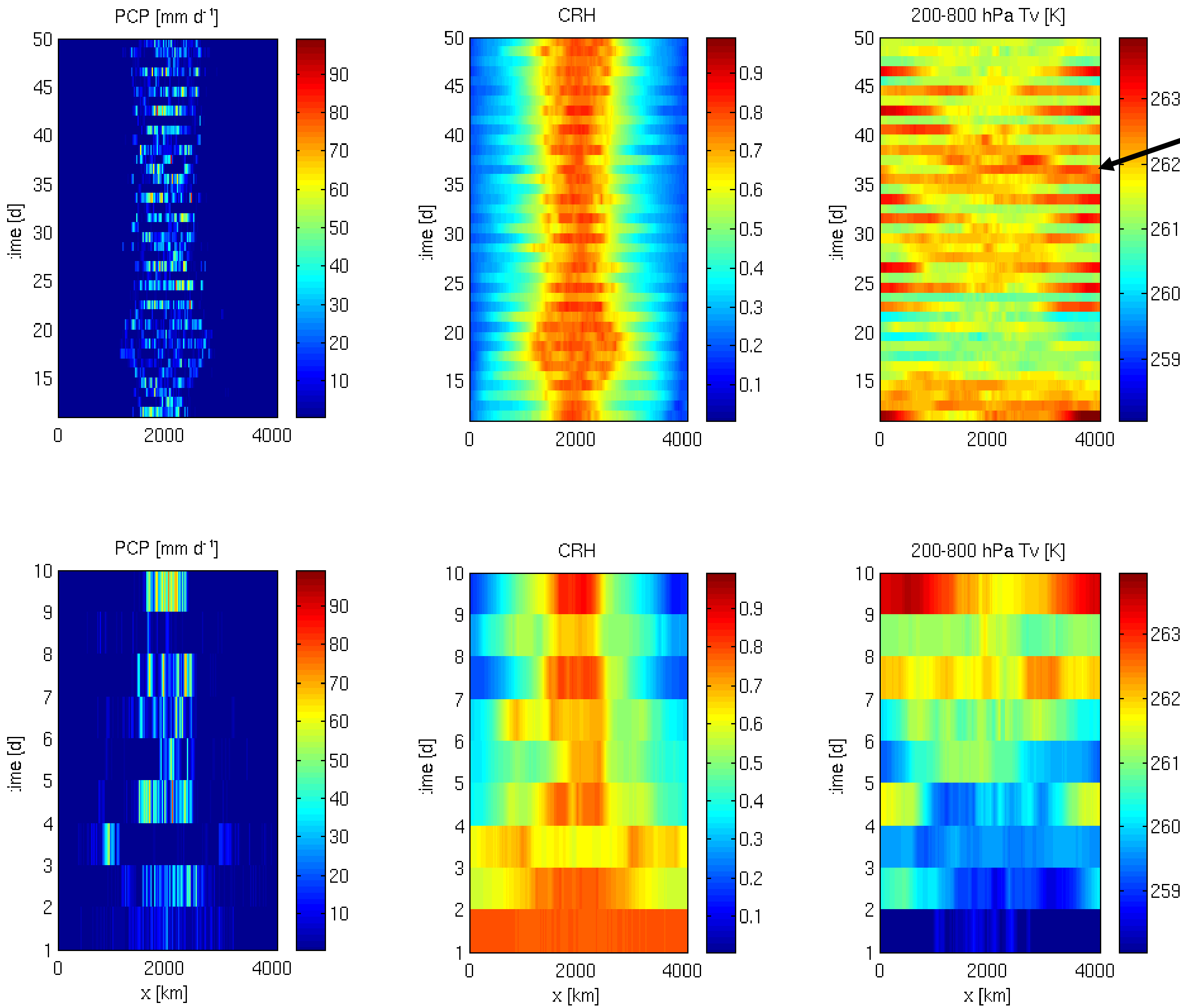
- No rotation, uniform insolation, periodic BCs
- Specified SST (°C) = 26, 28 – 2 cos($2\pi x/X$).

Our study (Bretherton et al. 2005, submitted to TCFD)

- SAM6.3 CRM (Khairoutdinov and Randall 2003)
- Bowling alley 4096 [1024] x 64 km, Δx = 2 km, 64 levels.
- Run out to steady state (50 days + 100 days for averaging)



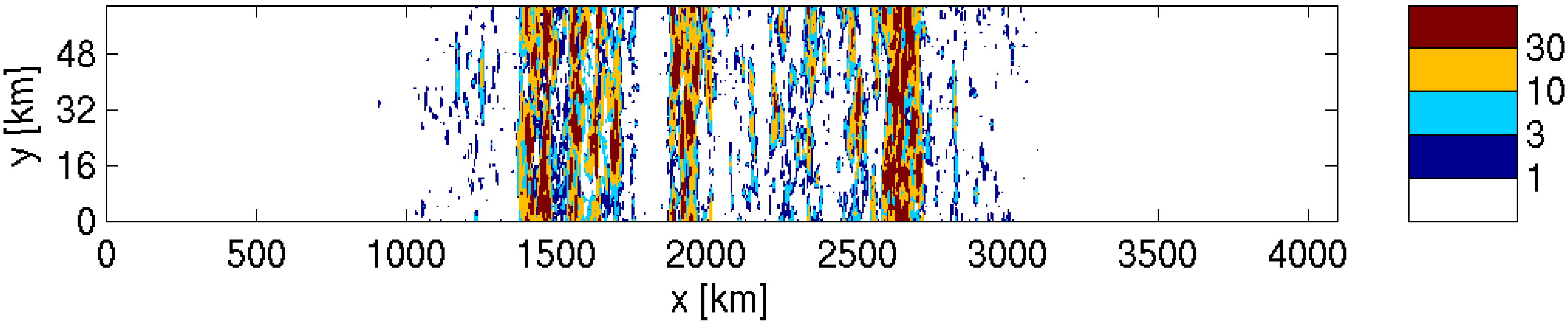
Approach to equilibrium



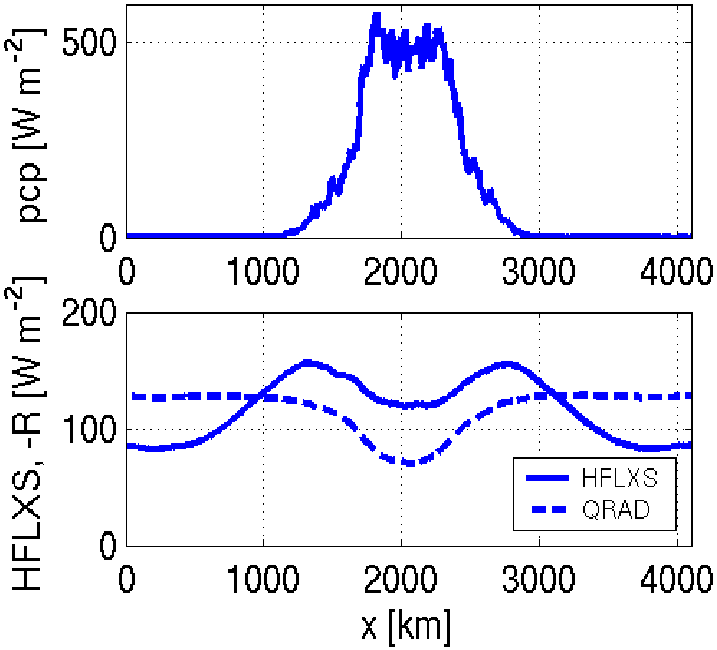
Standing internal waves

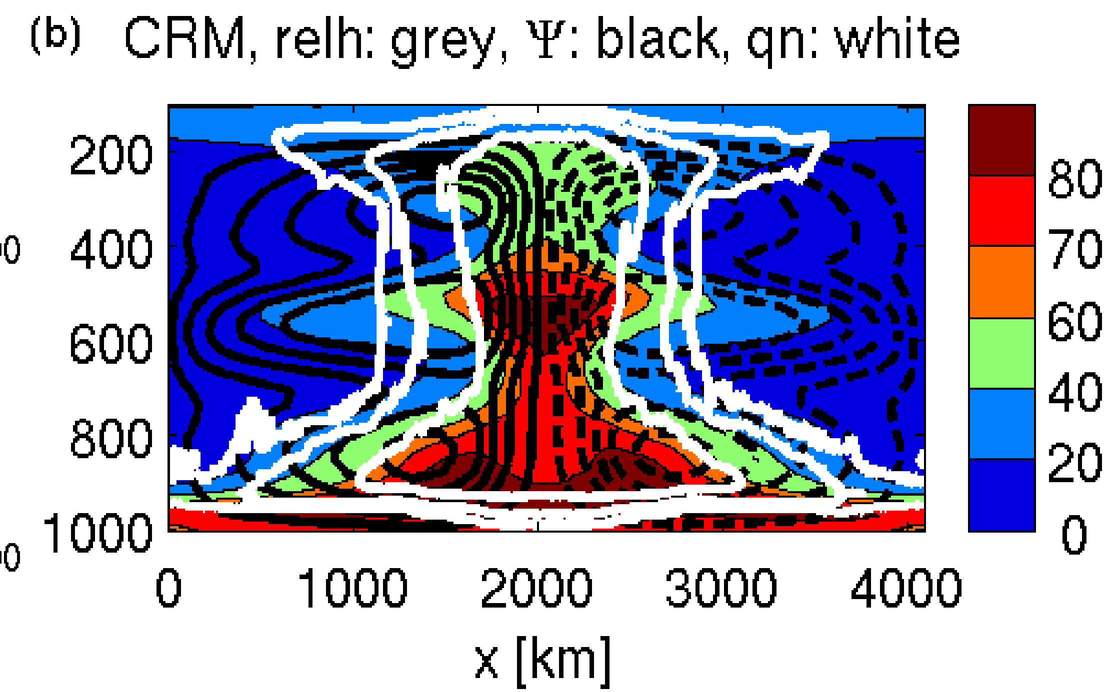
25d to thermal equilibrium after initial warming

Mean rainfall for day 50



50-150 day mean Walker circulation





Thermally direct circulation

What determines ascent region width, rainfall?

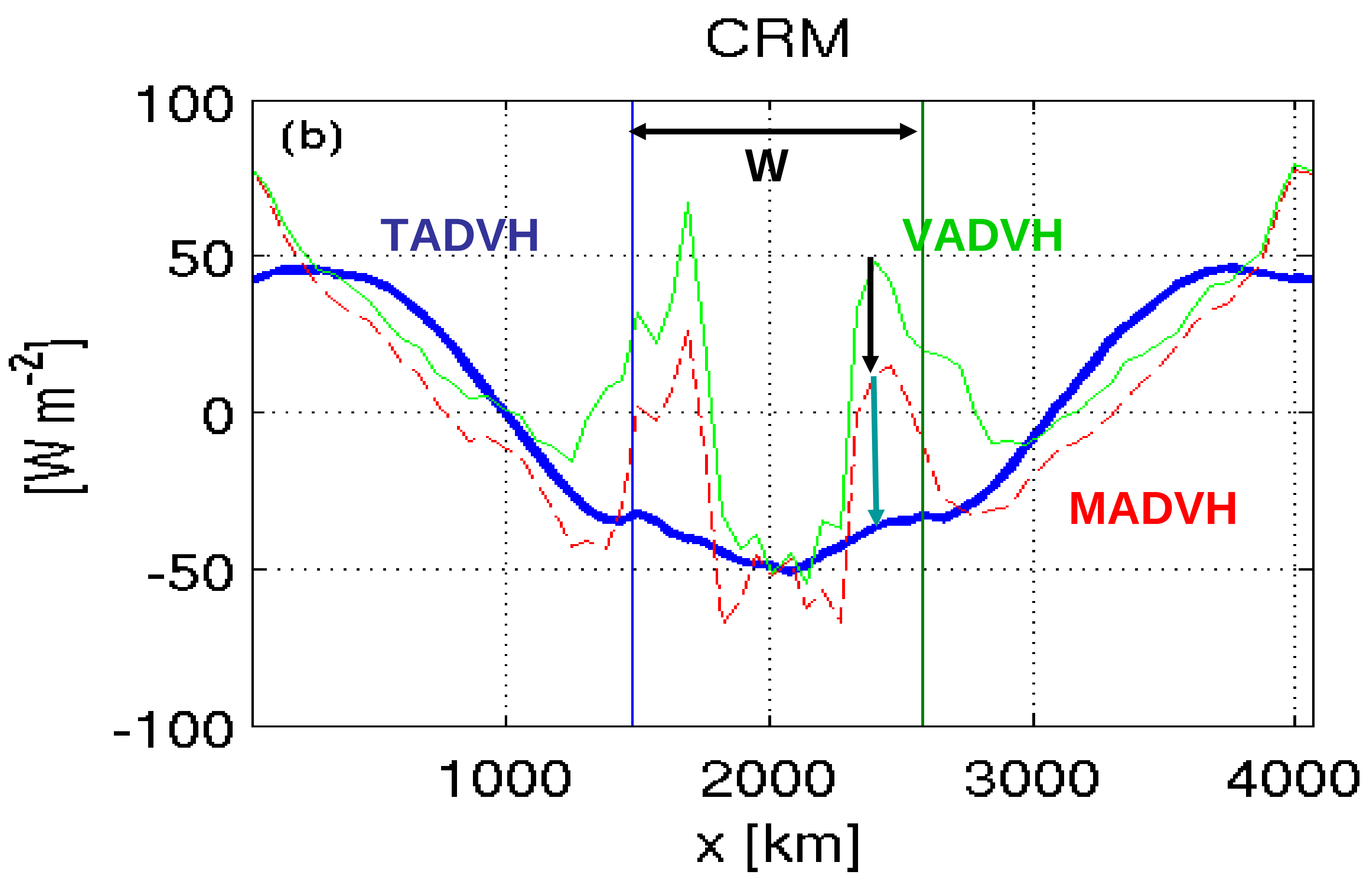
Steady-state MSE advection

0 = THF – ΔR + TADVH

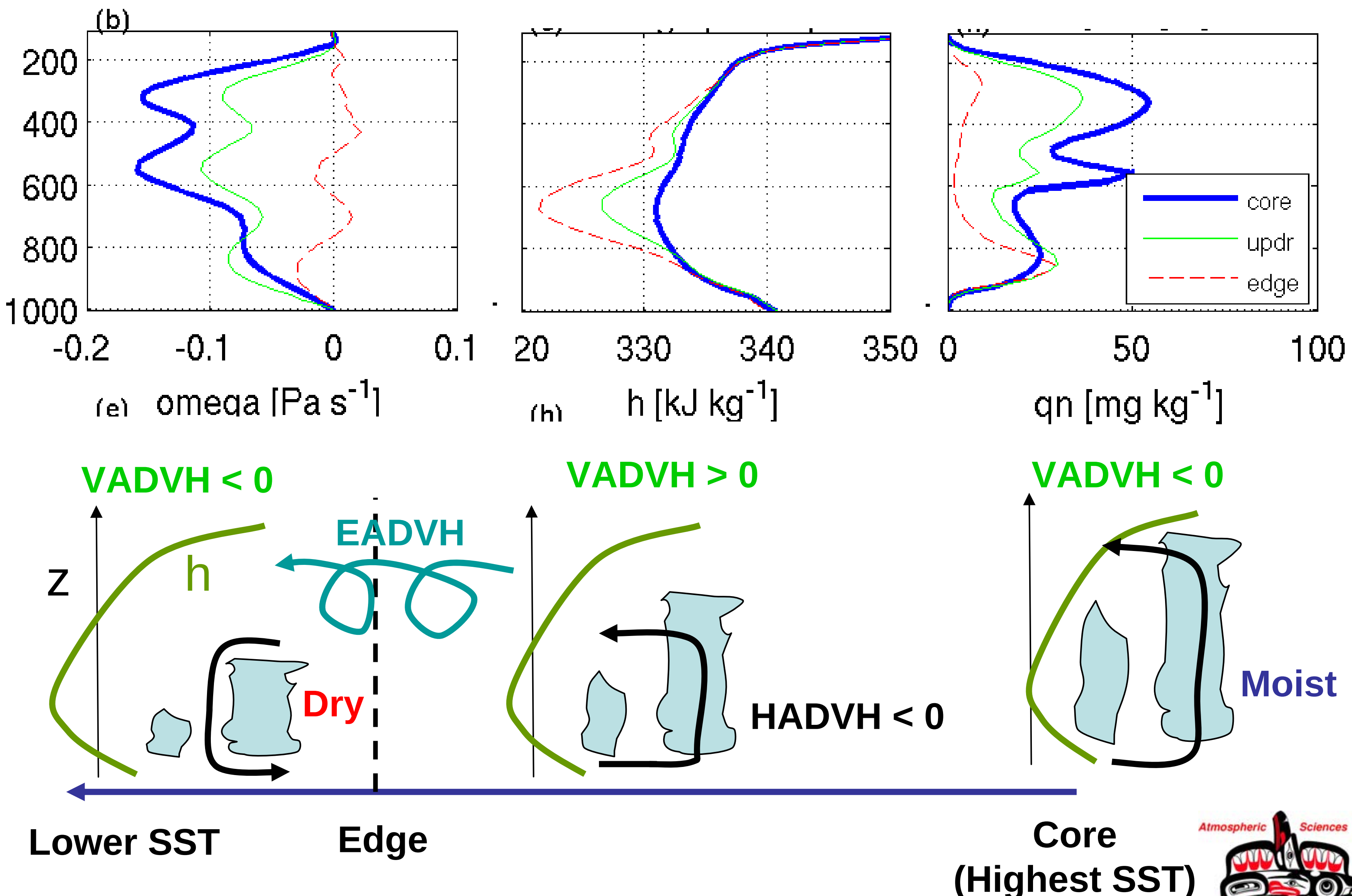
TADVH = MADVH + EADVH

MADVH = <-uh> = <-h∇·u> (VADVH) + <-u·∇h> (HADVH)

EADVH = <-u´h´>



Horizontal structure of the ascent region



Ascent-region average MSE/DSE budgets

Goal: Understand ascent region (<w> > 0) width W.

$$\text{MSE: } 0 = \langle LHF \rangle + \langle SHF \rangle - \langle \Delta R \rangle + \langle MADVH \rangle + \langle EADVH \rangle$$

$$\text{DSE: } 0 = L\langle P \rangle + \langle SHF \rangle - \langle \Delta R \rangle + \langle VADVS \rangle + \langle HADVS \rangle + \langle EADVS \rangle$$

Define ascent region moist stability ratio

$$\alpha = \underbrace{\langle MADVH \rangle / \langle VADVS \rangle}_{\alpha_M} + \underbrace{\langle EADVH \rangle / \langle VADVS \rangle}_{\alpha_E}$$

Then MSE + DSE $\Rightarrow$

$$L\langle P \rangle = \alpha^{-1}\left[\langle LHF \rangle + (1-\alpha)(\langle SHF \rangle - \langle \Delta R \rangle) \right]$$

Assuming that almost all rainfall is in ascent region,

$$W \cdot L\langle P \rangle = A \cdot \overline{LHF} \qquad \text{(rainfall = evaporation)}$$

so

$$W / A \approx \alpha / D \qquad D = \left[\langle LHF \rangle + (1-\alpha)(\langle SHF \rangle - \langle \Delta R \rangle) \right] / \overline{LHF}$$

(diabatic forcing)

Does this MSE diagnosis work?

For our simulation

W/A = 0.27

α_M = 0.08, α_E = 0.04 $\Rightarrow$ Moist stability ratio α = 0.12

Diabatic forcing D = 0.44

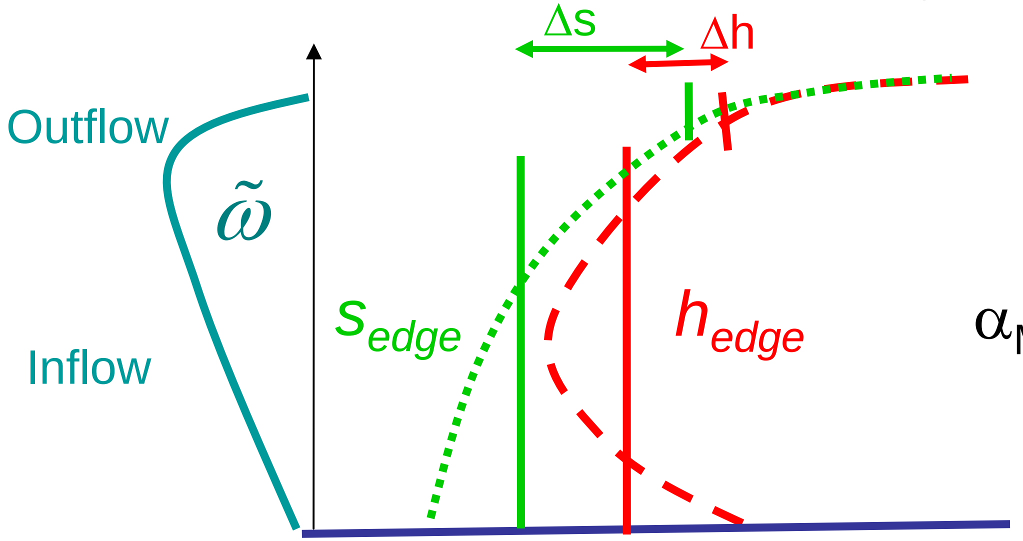
$(W/A)_{pred}$ = α/D =0.27 (good)

- Simulations with different A and/or SST_0 but the same ΔSST differ more in α than D, so α is key.
- Must understand α_M (α_E secondary unless A smaller).

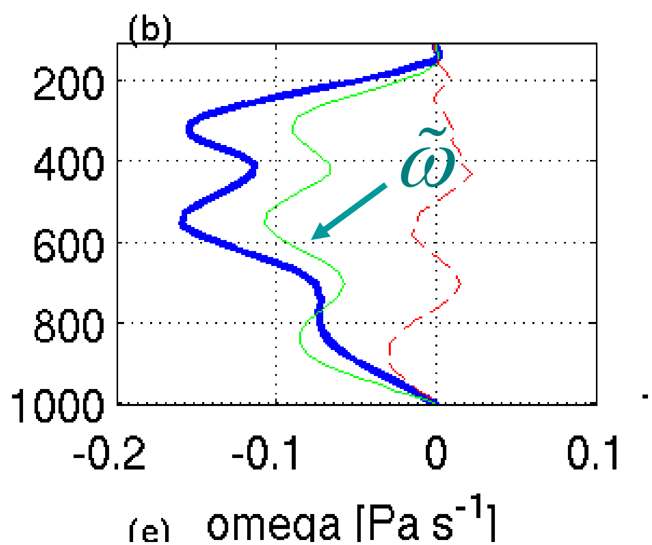
$$\alpha_M = \frac{MADVH}{VADVS} = \frac{-\int_{p_T}^{p_s} \partial(uh)/\partial x dp}{-\int_{p_T}^{p_s} s\partial u/\partial x dp} = \frac{\int_{p_T}^{p_s} \omega\partial h_{edge}/\partial p \cdot dp}{\int_{p_T}^{p_s} \omega\partial\tilde{s}/\partial p \cdot dp}$$

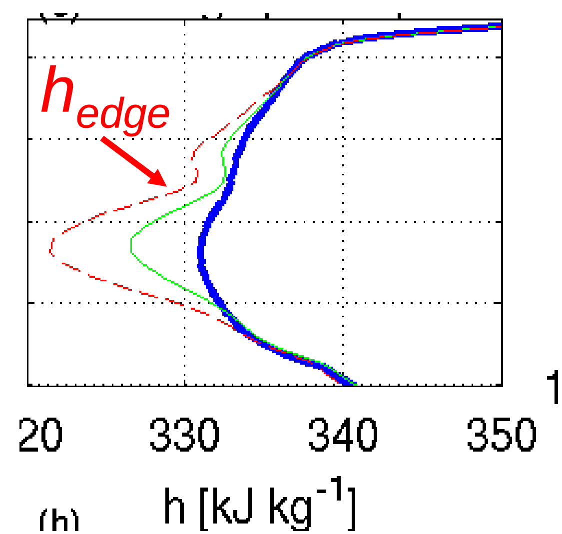
Understanding α_M

- Larger α_M if either ω top-heavy or ***h_{edge}* bottom-heavy**



$\alpha_M = \Delta h/\Delta s$

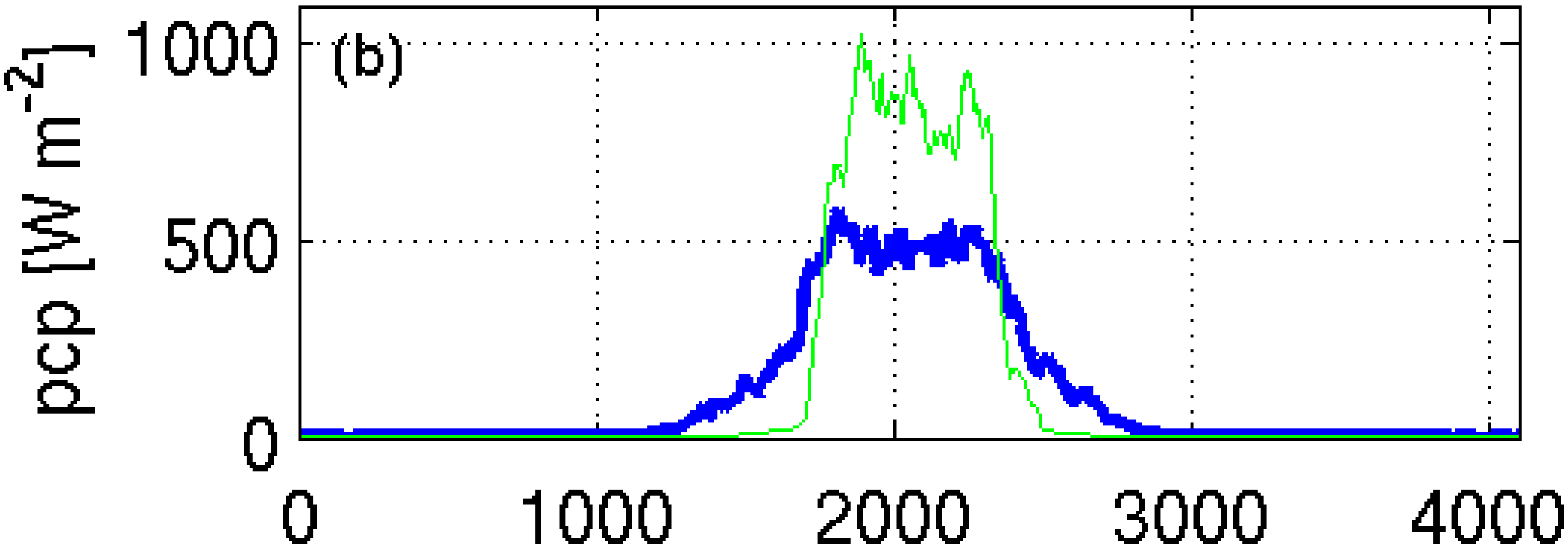




ω-wiggles contribute significantly to α.

Atmospheric Sciences
University of Washington

SST+2 case vs. control



- Ascent-region width narrows, rainfall increases.
- Explainable with MSE reasoning?

$W/A = \alpha/D$, $\alpha_M = 0.01$, $\alpha_E = 0.04$, $D = 0.30$, $W/A = 0.17$

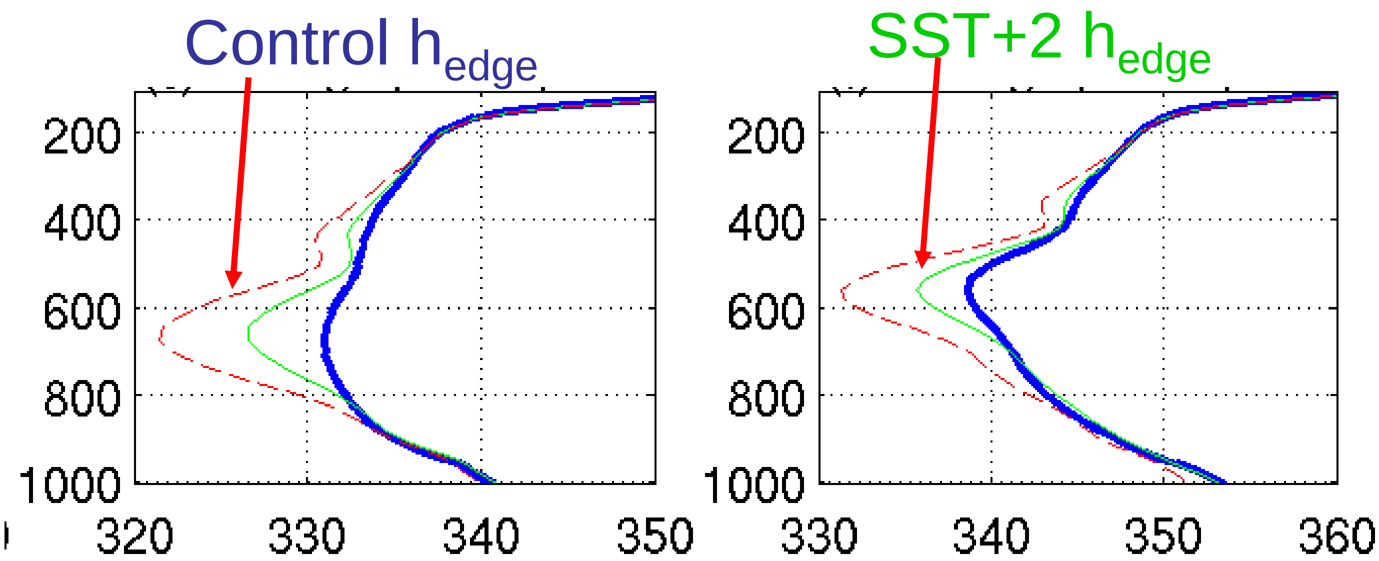
($\alpha_M = 0.08$, $\alpha_E = 0.04$, $D = 0.44$, $W/A = 0.27$)

- Decreased width associated with smaller α_M

Atmospheric Sciences
University of Washington

Why does SST+2 have lower moist stability?

- Decreased moist stability α_M reflects less bottom-heavy h_{edge}



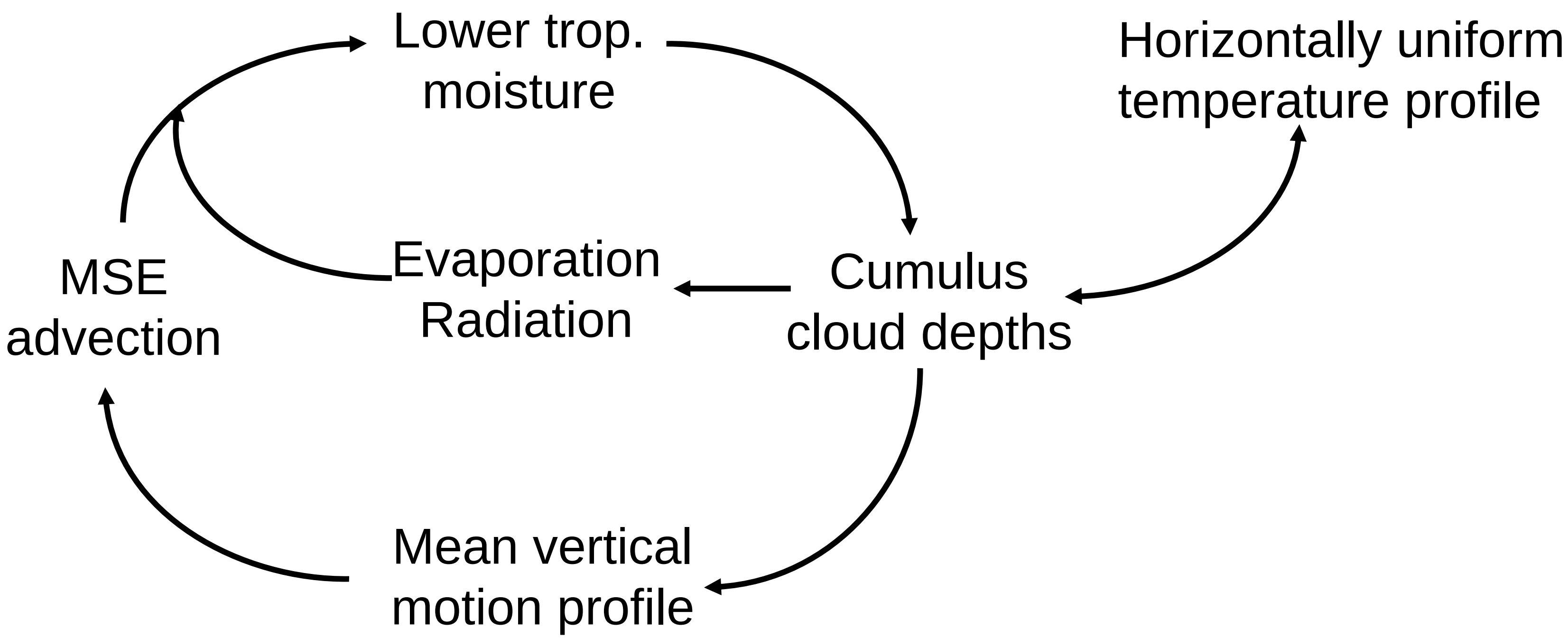
Two speculative reasons:

- More radiative cooling in SST+2 destabilizes h profile
- Higher freezing level moves up h minimum.

This type of reasoning can help us understand the response of tropical ITCZ regions to climate change.

Conclusions

- Over warm oceans, moisture-convection feedbacks fundamental to transient convection and mean rainfall.



- Column moist static energy budgets are a fruitful approach to understanding these feedbacks.