Radiative-Convective Instability

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Self-Aggregation of Deep Moist Convection

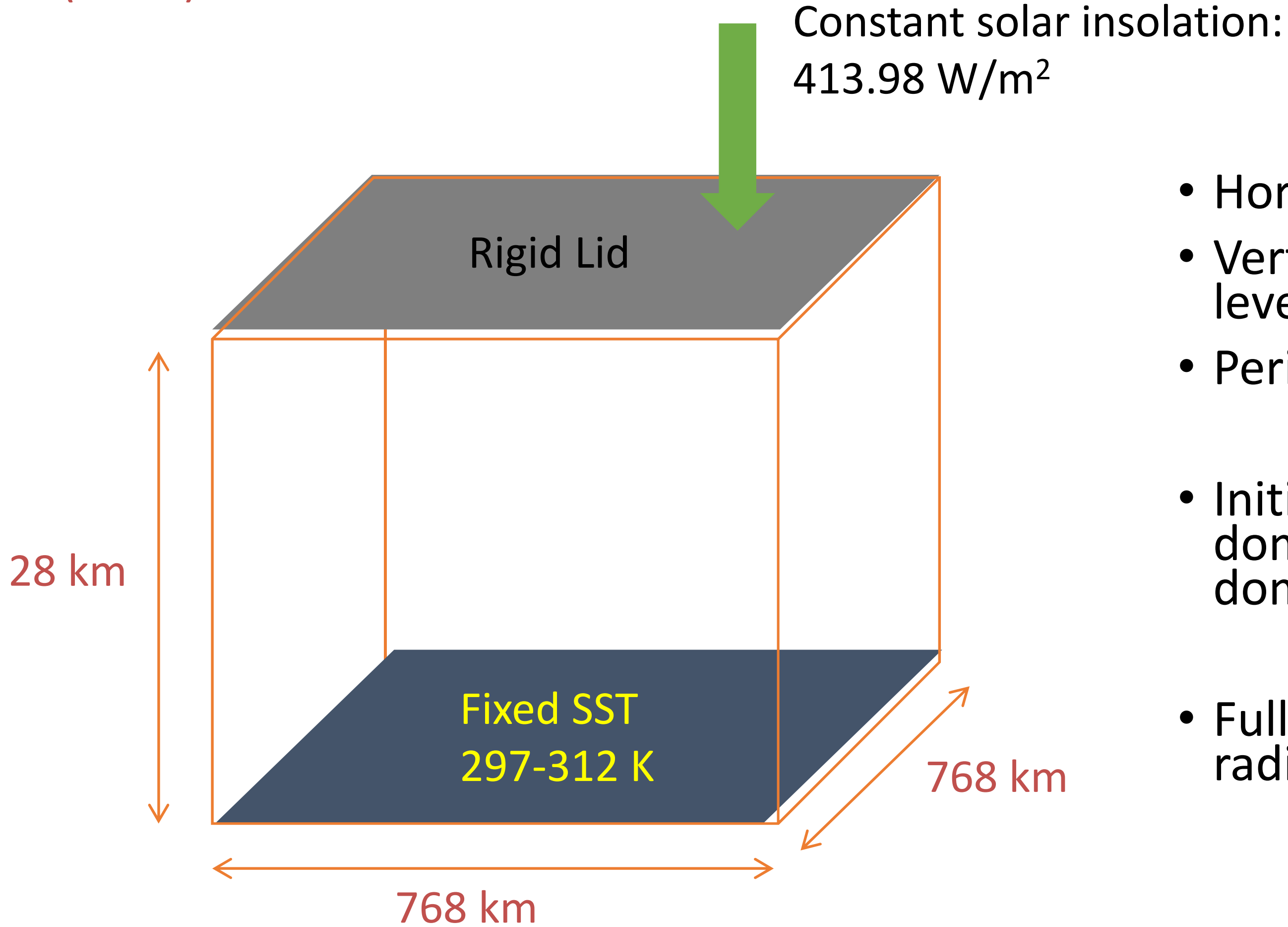
- Cloud Clusters
- Tropical Cyclone Genesis
- The MJO

1. Explicit Simulation of Radiative-Convective Equilibrium

(Work of Allison Wing, and with much help from Marat Khairoutdinov)

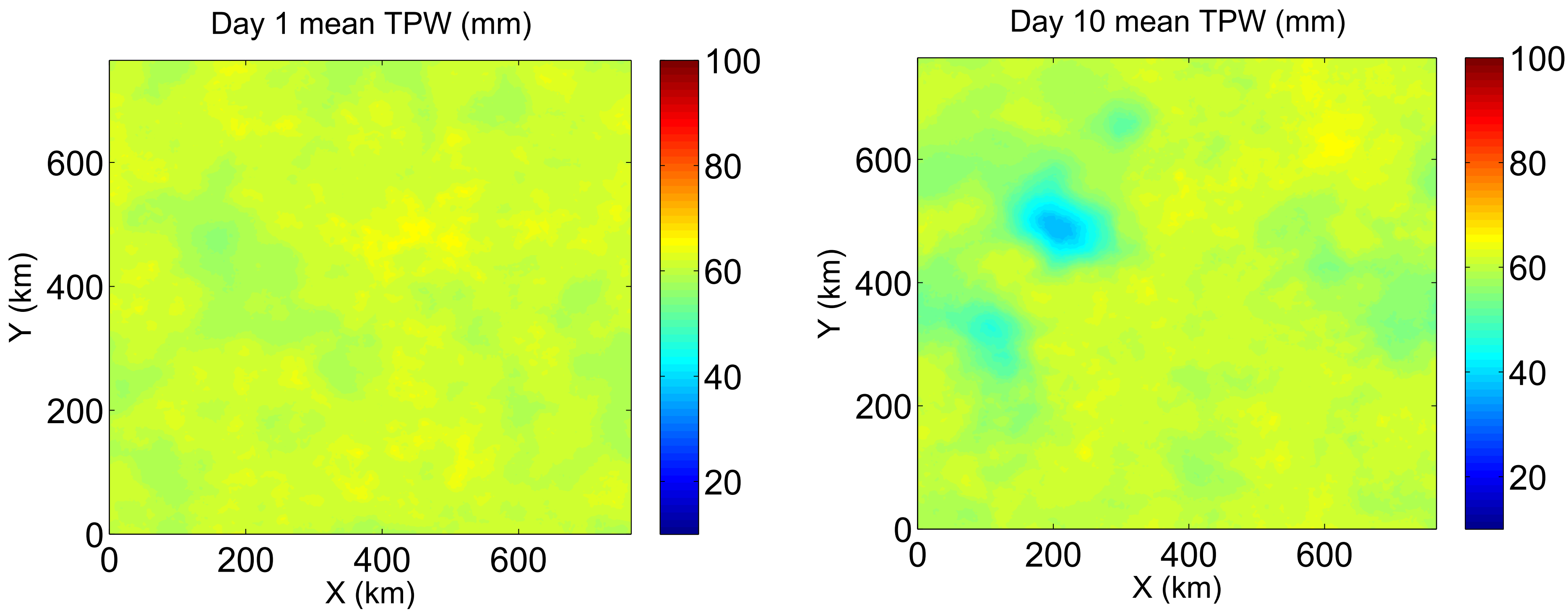
Approach: Idealized modeling of convective organization in radiative-convective equilibrium using a cloud resolving model

System for Atmospheric Modeling (SAM) of Khairoutdinov and Randall (2003)



- Horizontal Resolution: 3km
- Vertical Resolution: 64 levels
- Periodic lateral boundaries
- Initial sounding from domain average of smaller domain run in RCE
- Fully interactive RRTM radiation and surface fluxes.

Evolution of Vertically Integrated Water Vapor



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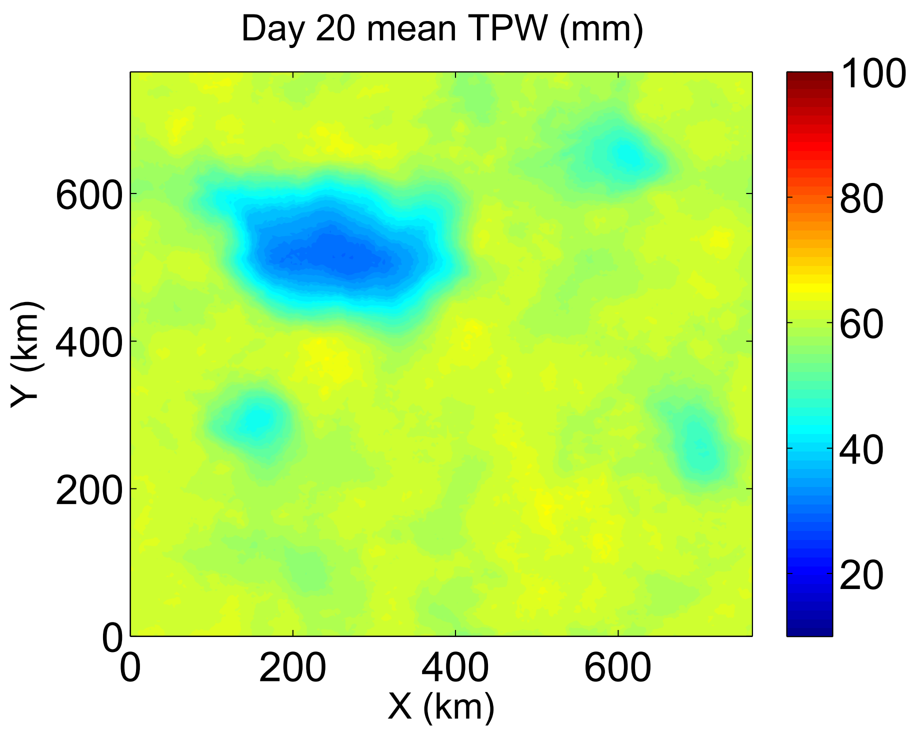

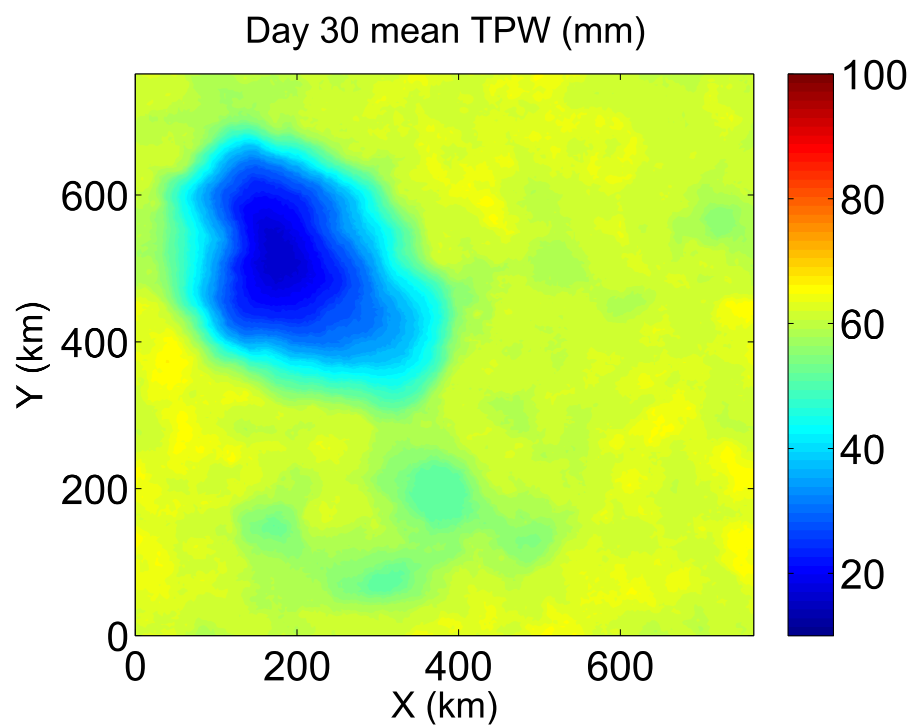

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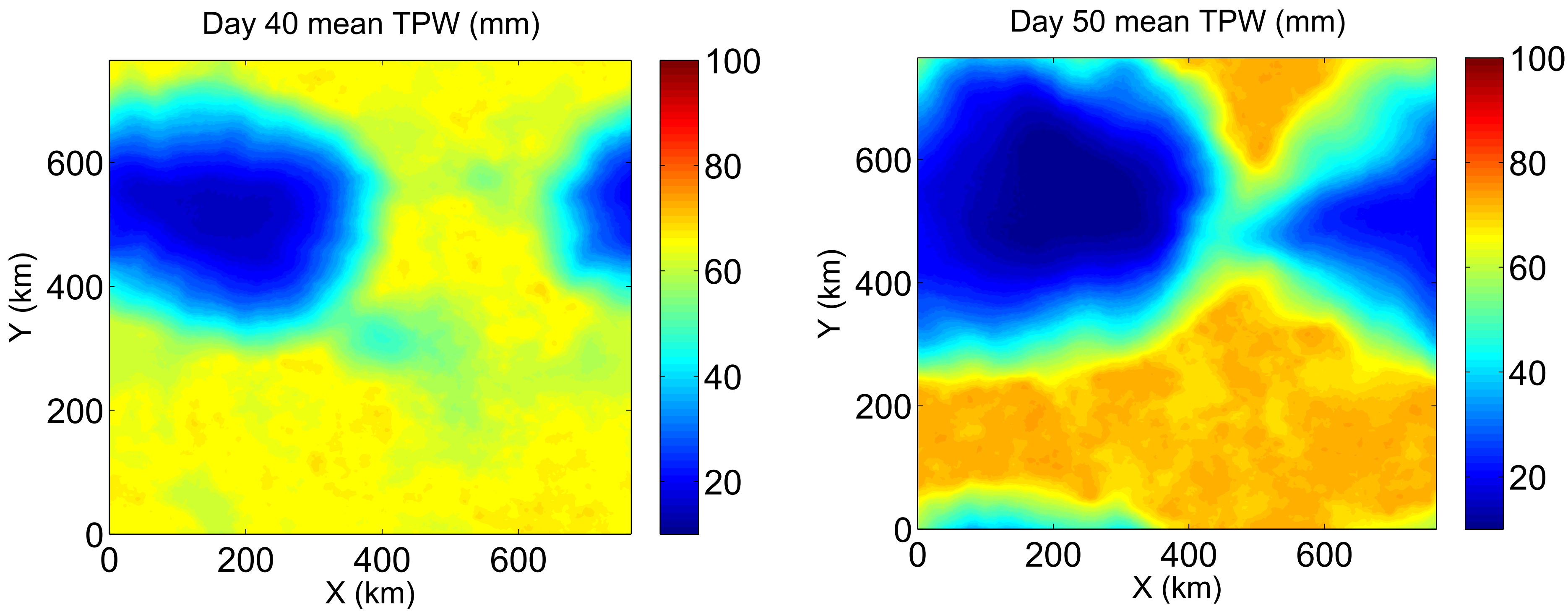
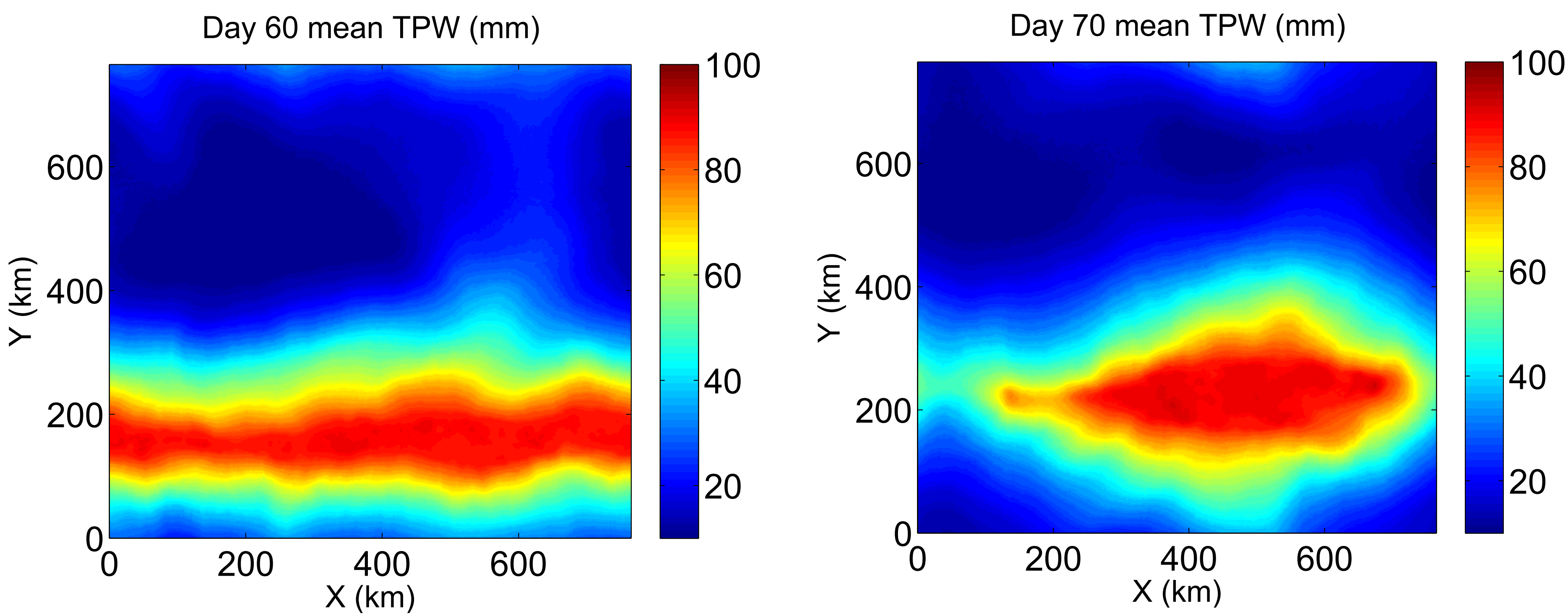
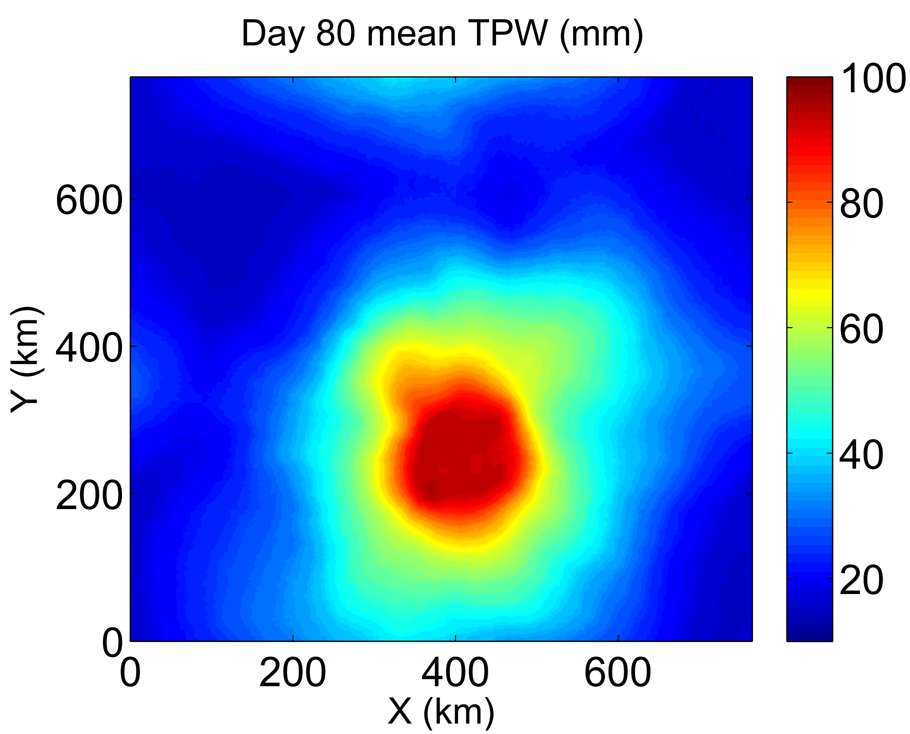
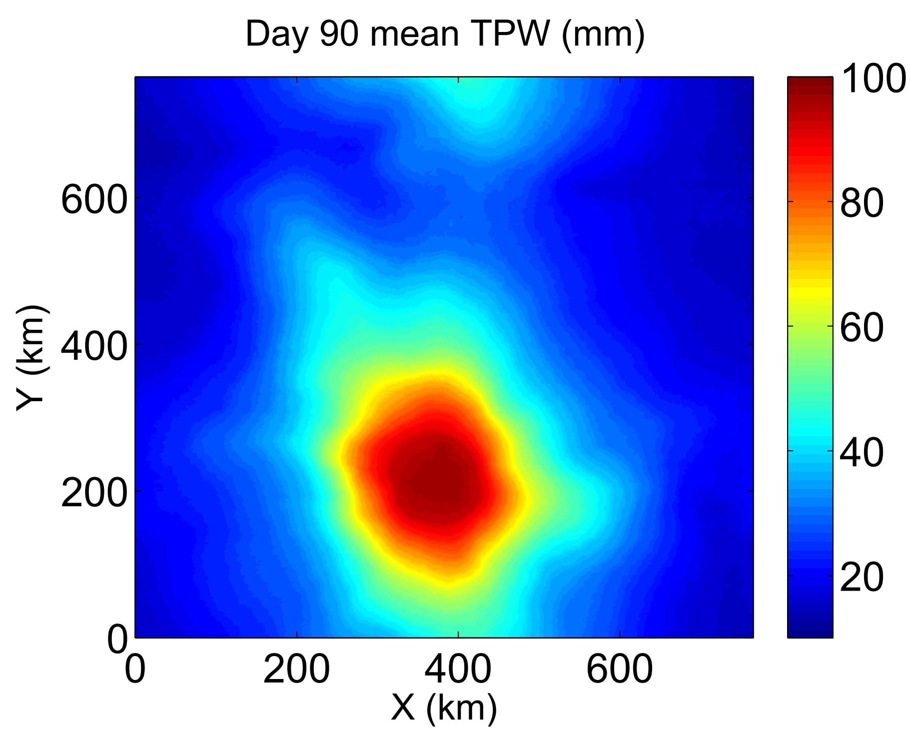


Evolution of Vertically Integrated Water Vapor



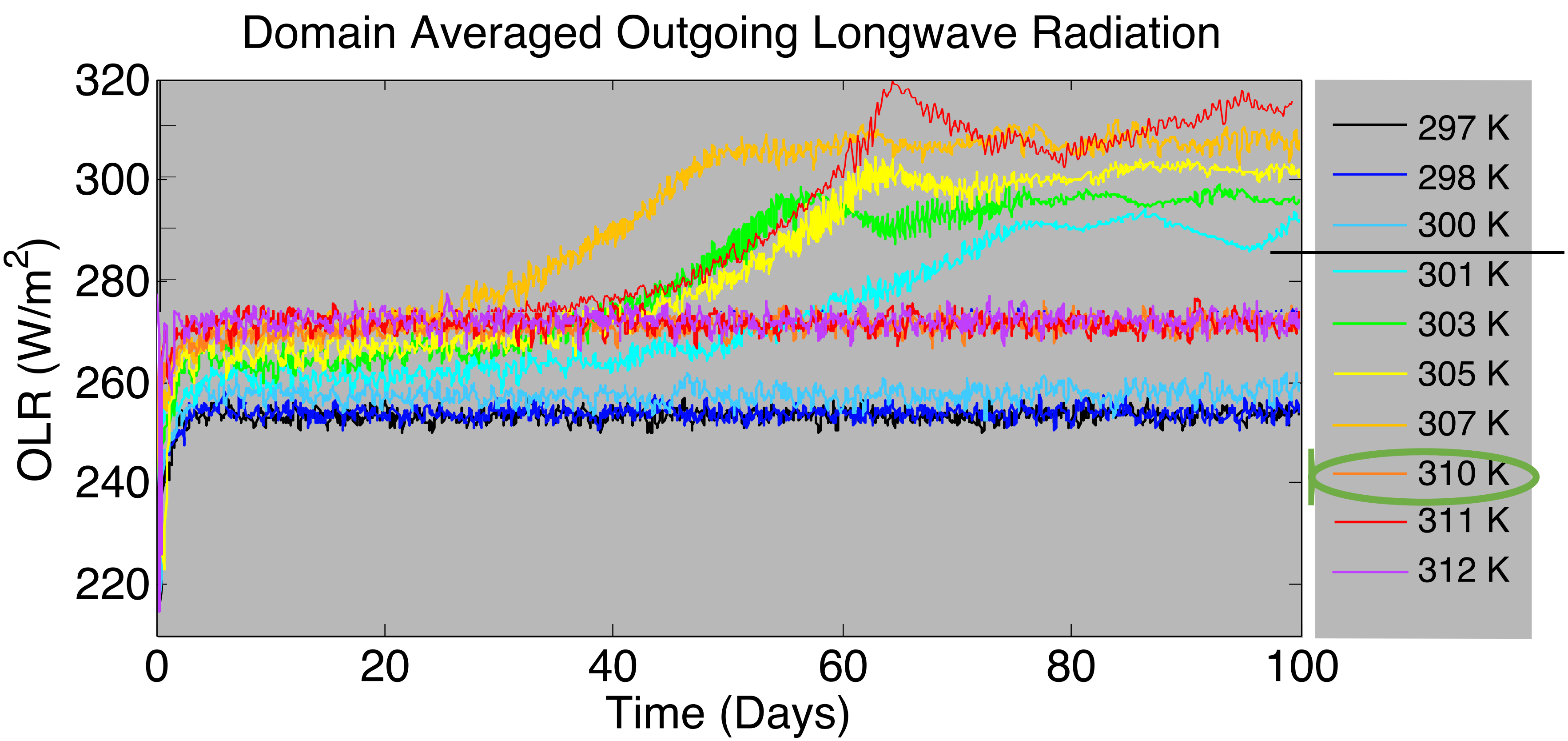
Evolution of Vertically Integrated Water Vapor





Monsoonal Thunderstorms, Bangladesh and India, July 1985

Surface Temperature Dependence



Larger domain needed for high SSTs to aggregate

Analysis of Feedback Terms

Framework: Budget for spatial variance of column integrated **frozen moist static energy**

- Consider anomalies from the horizontal mean (primes)

$$\frac{1}{2}\frac{\partial \hat{h}'^2}{\partial t} = \hat{h}'\mathrm{LHF}' + \hat{h}'\mathrm{SHF}' + \hat{h}'\mathrm{NetSW}' + \hat{h}'\mathrm{NetLW}' - \hat{h}'\nabla \cdot \widehat{\vec{u}h}$$

Feedback term: FMSE anom * Diabatic term anom

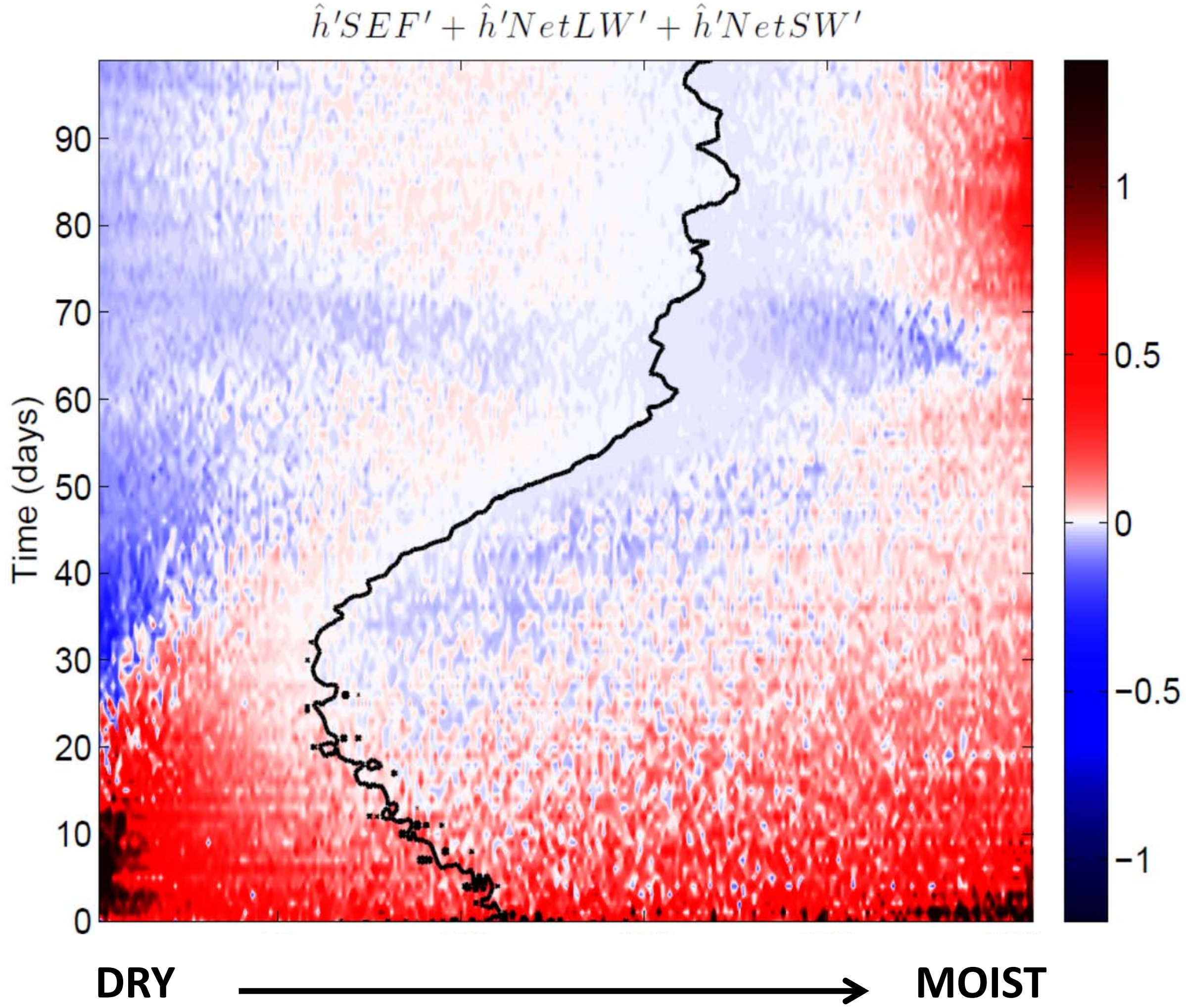
Positive Feedback: Process increases FMSE of already moist region

Negative Feedback: Process decreases FMSE of moist region

Total Diabatic Feedback Term

All terms normalized by

$h'^2/\Delta t$

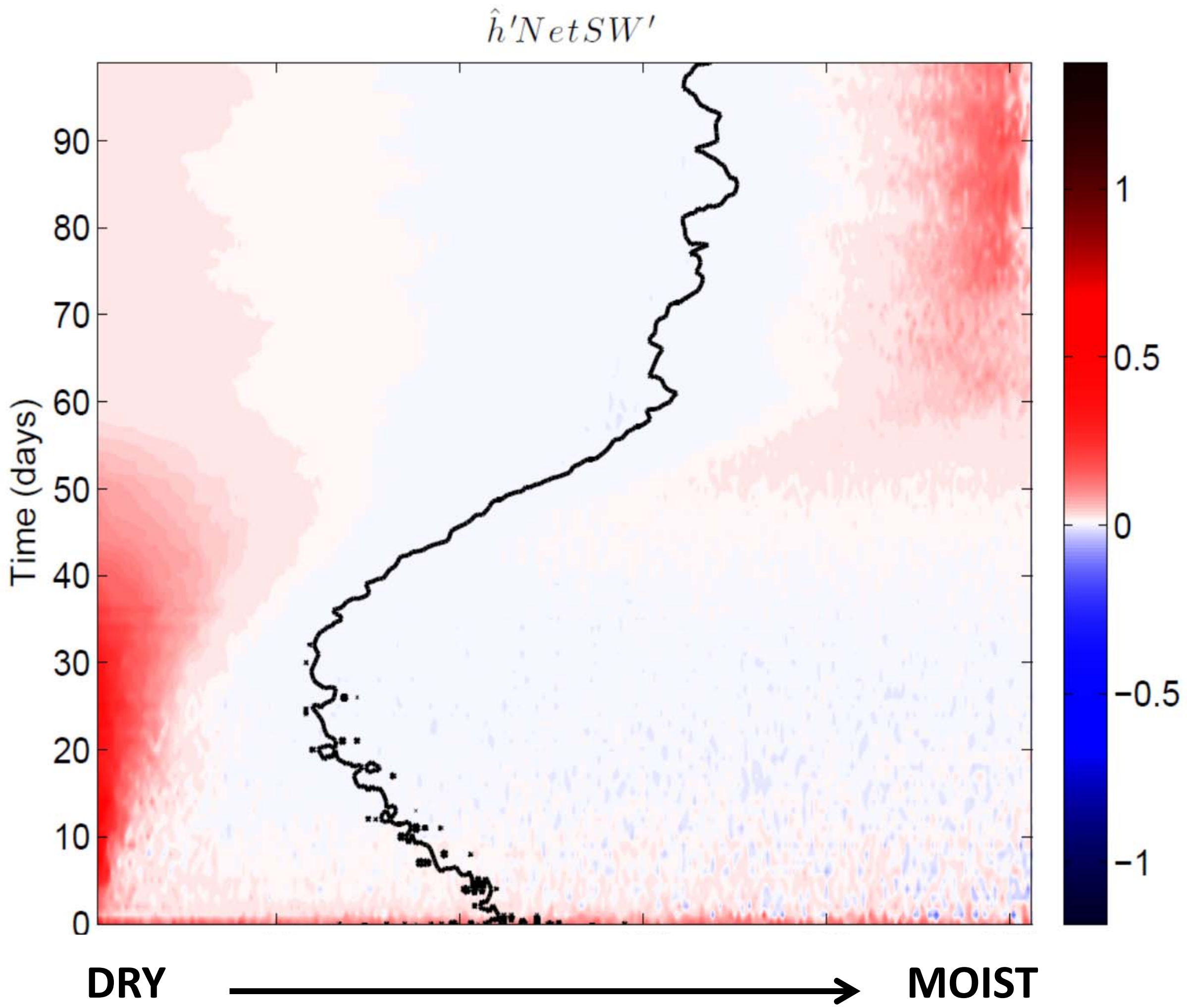


Black line:

$\hat{h}' = 0$

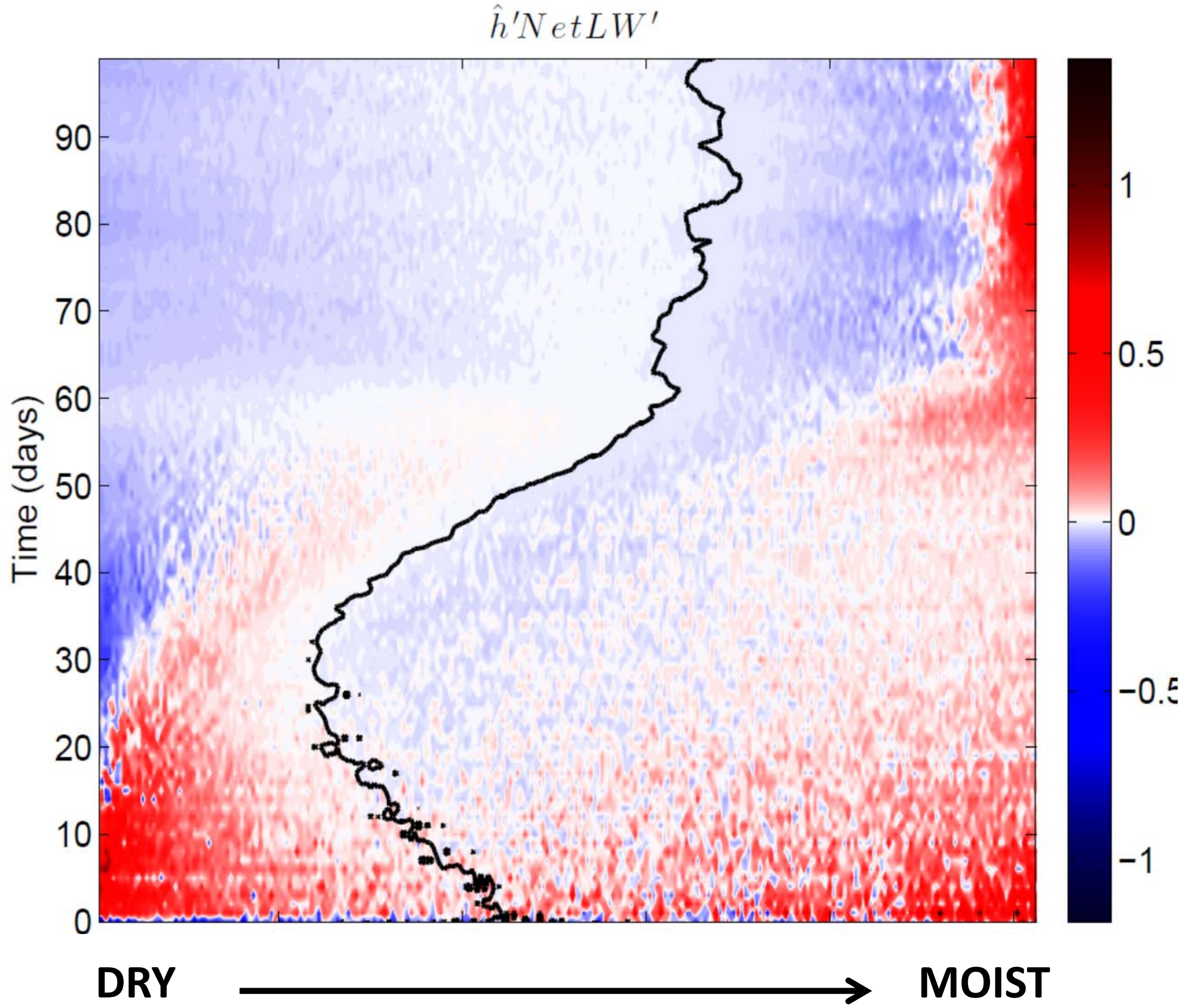
$$\frac{1}{2}\frac{\partial \hat{h}'^2}{\partial t} = \hat{h}'\mathrm{LHF}' + \hat{h}'\mathrm{SHF}' + \hat{h}'\mathrm{NetSW}' + \hat{h}'\mathrm{NetLW}' - \hat{h}'\nabla \cdot \widehat{\vec{u}h}$$

Column Shortwave Flux Convergence



$$\frac{1}{2}\frac{\partial \hat{h}'^2}{\partial t} = \hat{h}'\mathrm{LHF}' + \hat{h}'\mathrm{SHF}' + \hat{h}'\mathrm{NetSW}' + \hat{h}'\mathrm{NetLW}' - \hat{h}'\nabla \cdot \widehat{\vec{u}h}$$

Column Longwave Flux Convergence



$$\frac{1}{2}\frac{\partial \hat{h}'^2}{\partial t} = \hat{h}'\mathrm{LHF}' + \hat{h}'\mathrm{SHF}' + \hat{h}'\mathrm{NetSW}' + \hat{h}'\mathrm{NetLW}' - \hat{h}'\nabla \cdot \widehat{\vec{u}h}$$

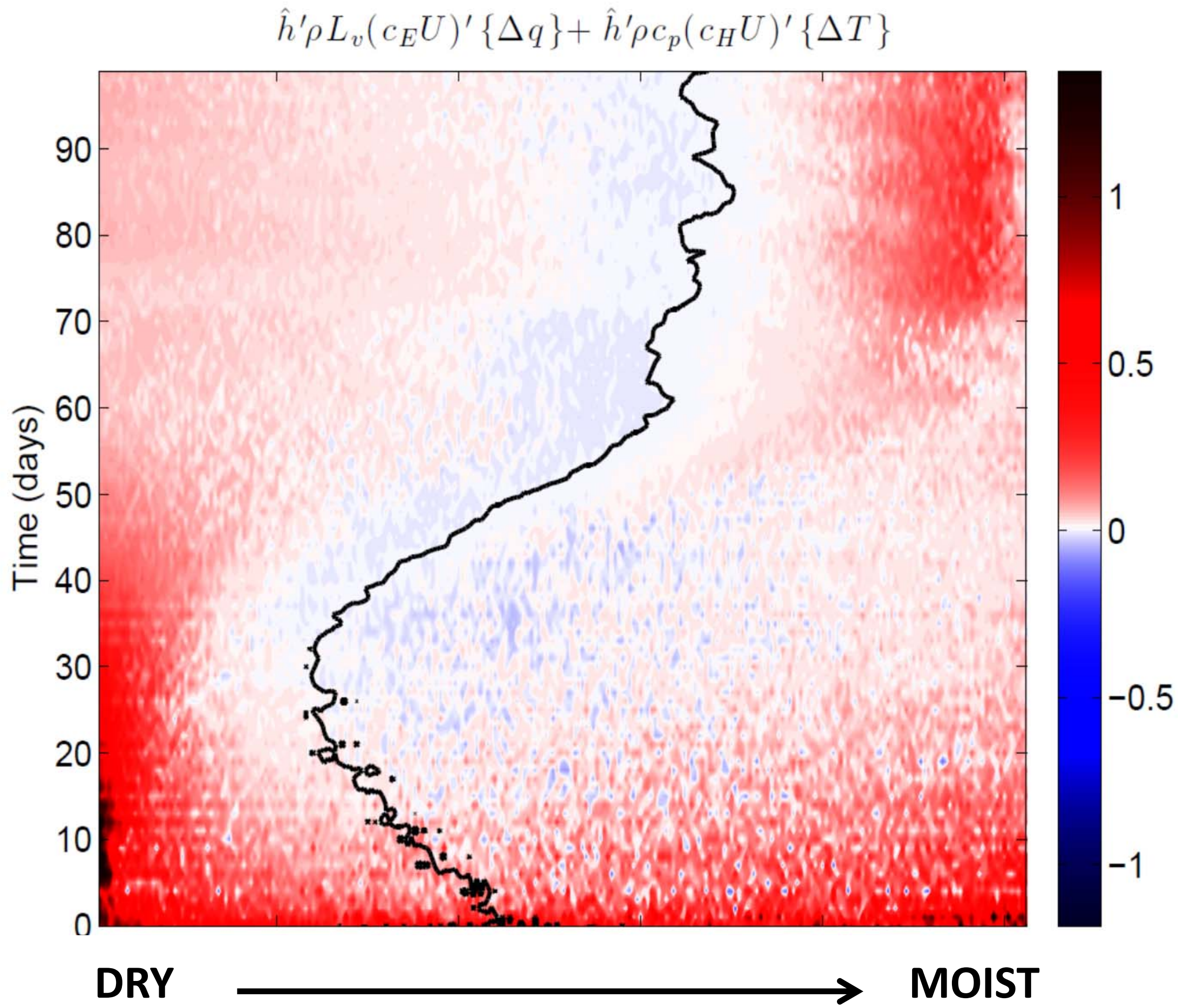
Surface Enthalpy Flux Partitioning

$$\mathrm{LHF} = \rho c_E L_v U \left(q^*_{T_s} - q_v\right)$$

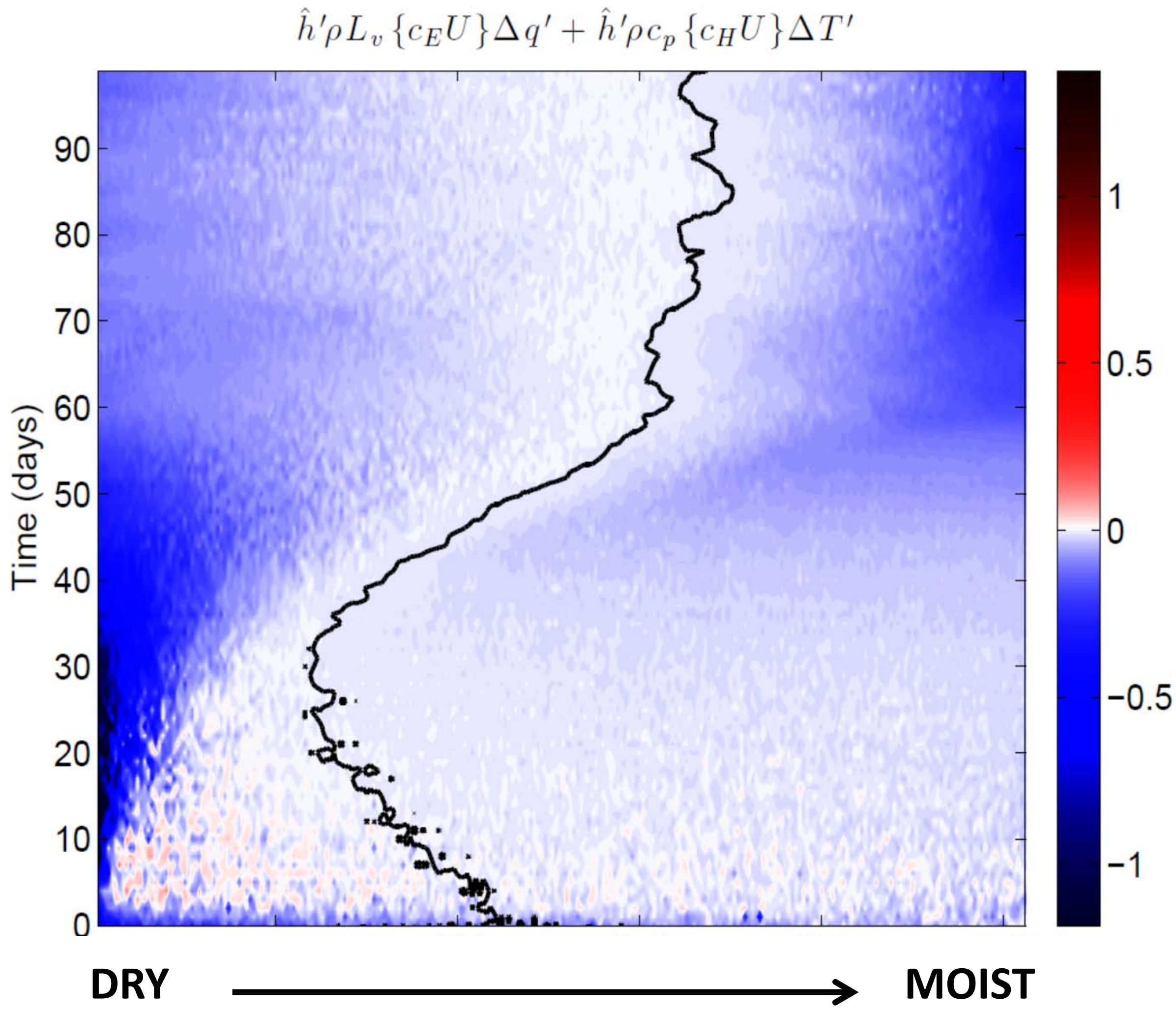
$$\mathrm{SHF} = \rho c_H c_p U \left(T_s - T_a\right)$$

- Partition surface enthalpy flux anomalies into
  - part due to U’
  - part due to Δq’ or ΔT’
  - part due to U’Δq’ or U’ΔT’

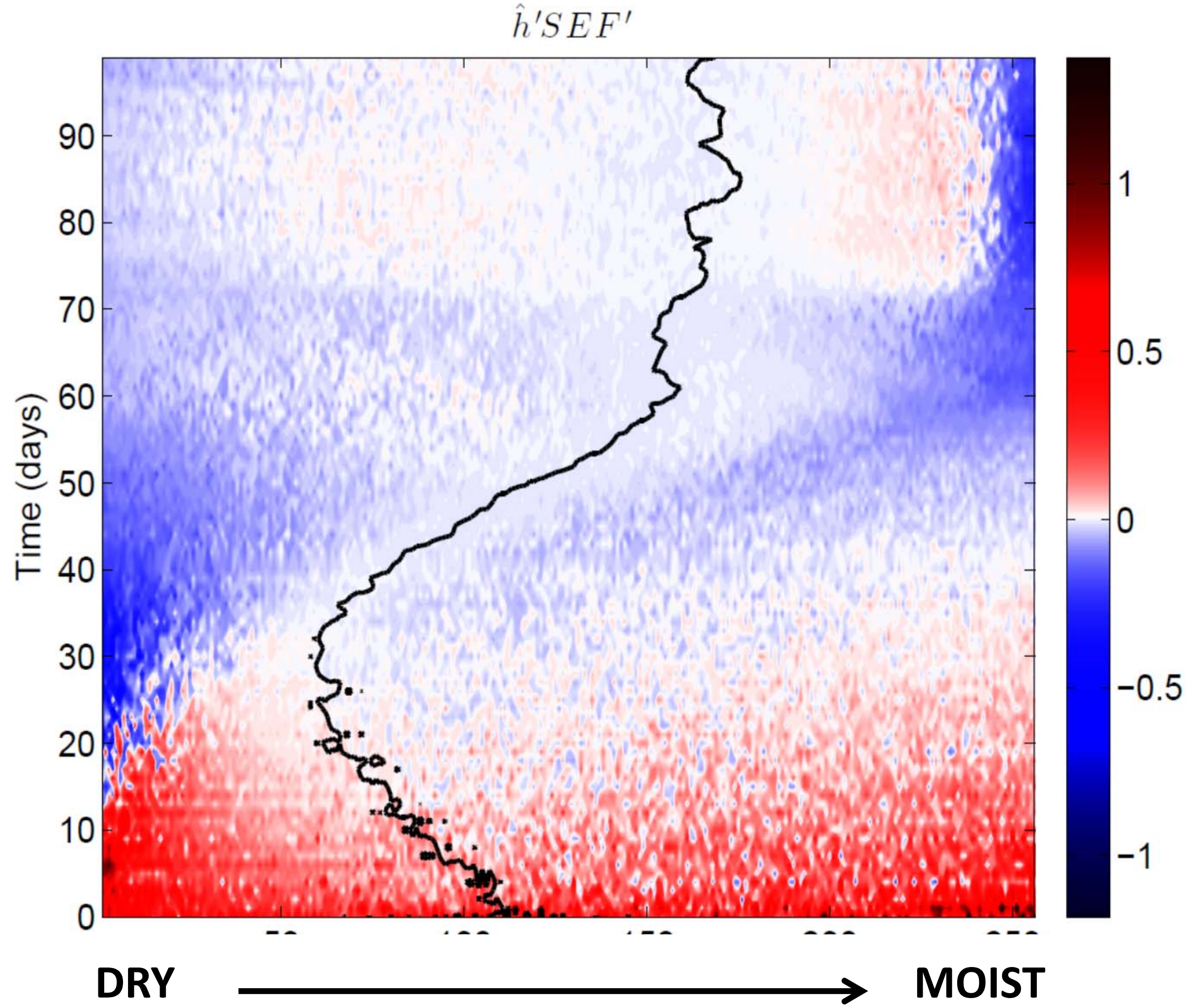
Surface Flux – Wind Feedback Term



Surface Flux –Air-Sea Disequilibrium Feedback Term

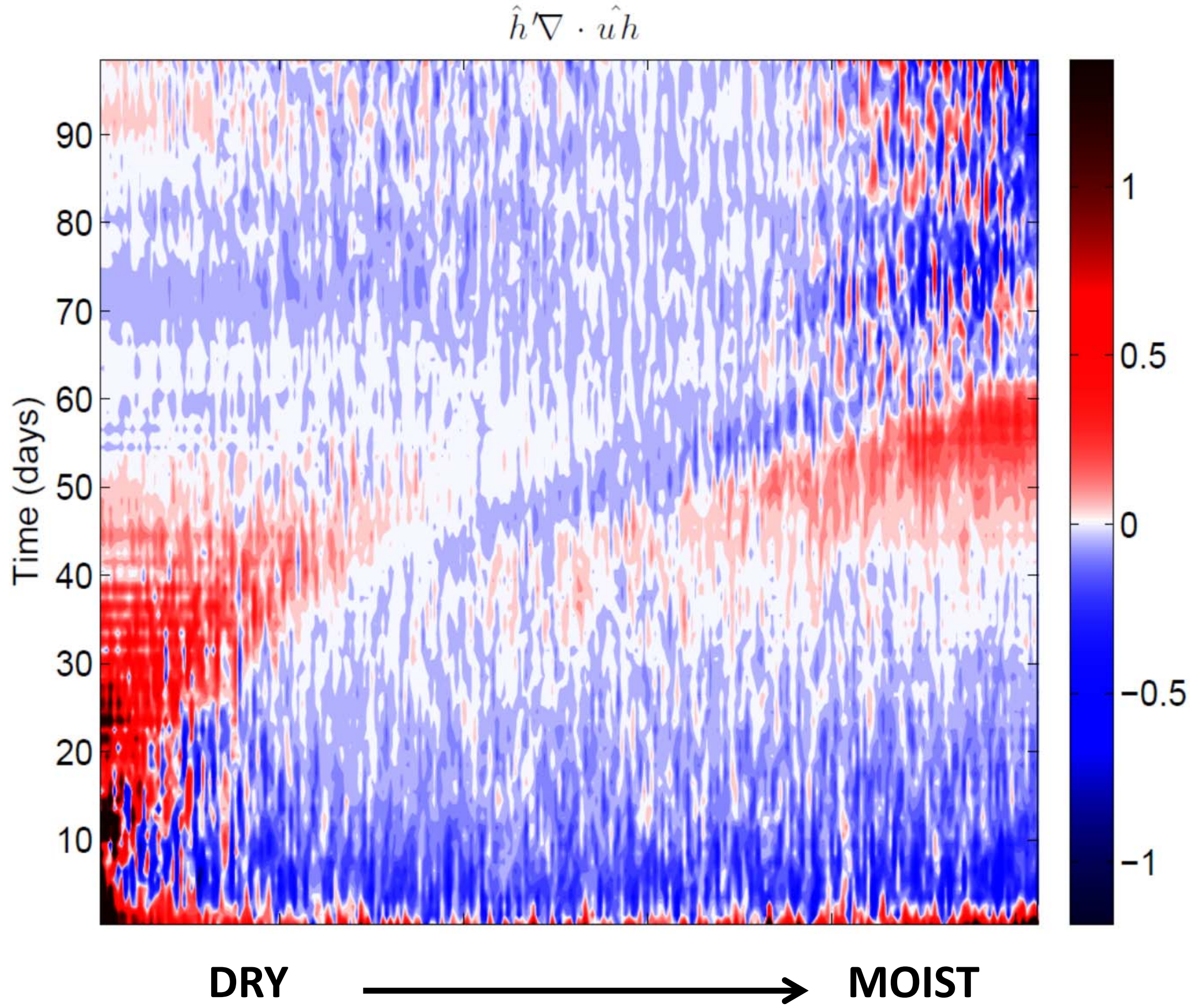


Total Surface Flux Feedback Term



$$\frac{1}{2}\frac{\partial \hat{h}'^2}{\partial t} = \boxed{\hat{h}'\mathrm{LHF}' + \hat{h}'\mathrm{SHF}'} + \hat{h}'\mathrm{NetSW}' + \hat{h}'\mathrm{NetLW}' - \hat{h}'\nabla \cdot \widehat{\vec{u}h}$$

Convergence Term



2. Single-Column Model

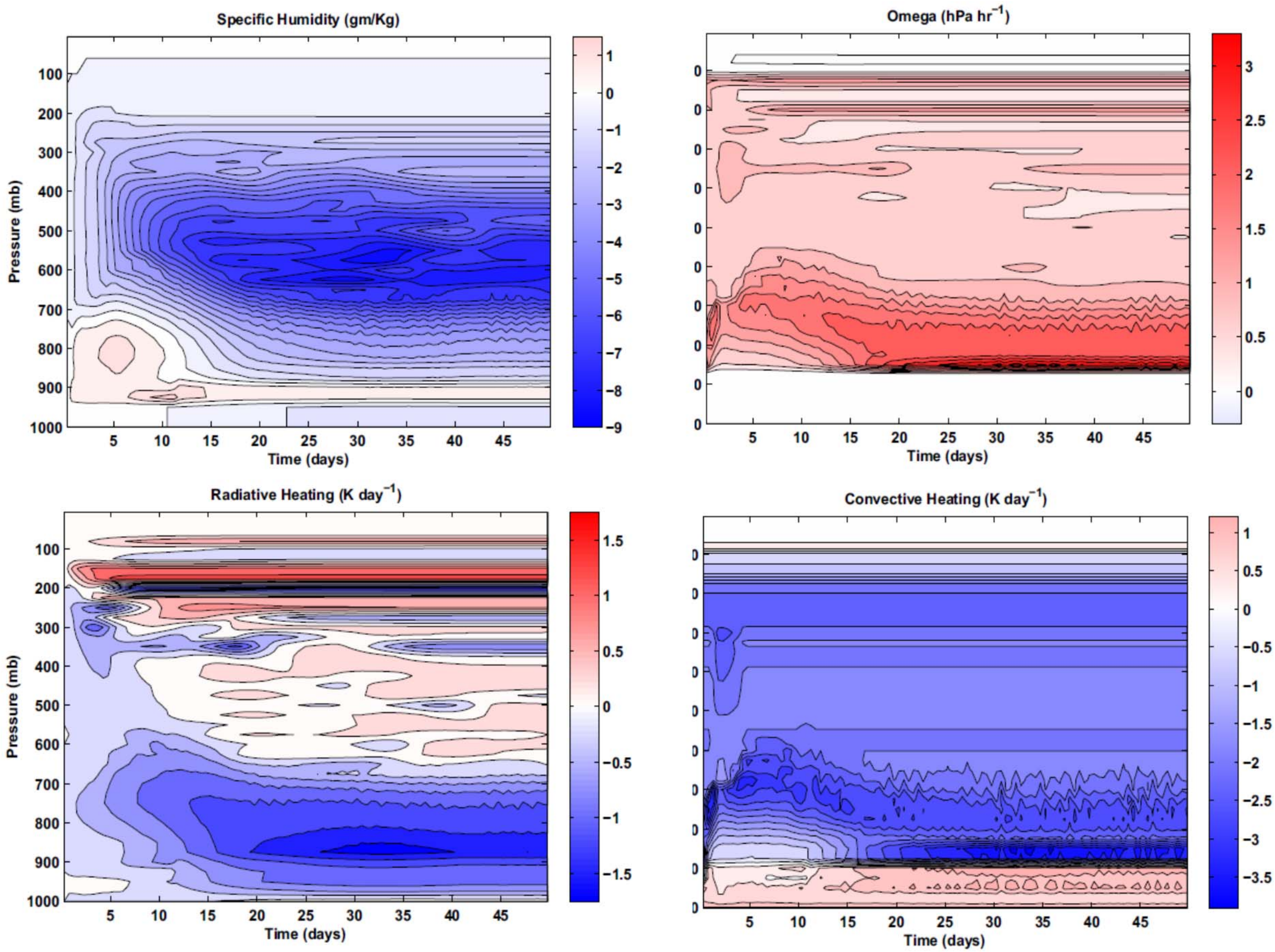
- MIT Single-Column Model
- Fouquart and Bonnel shortwave radiation, Morcrette longwave
- Emanuel-Zivkovic-Rothman convection
- Bony-Emanuel cloud scheme
- 25 hPa level spacing in troposphere; higher resolution in stratosphere
- Run into RCE state with fixed SST, then re-initialized in WTG mode with T fixed at 850 hPa and above; small perturbations to w in initial condition

Results

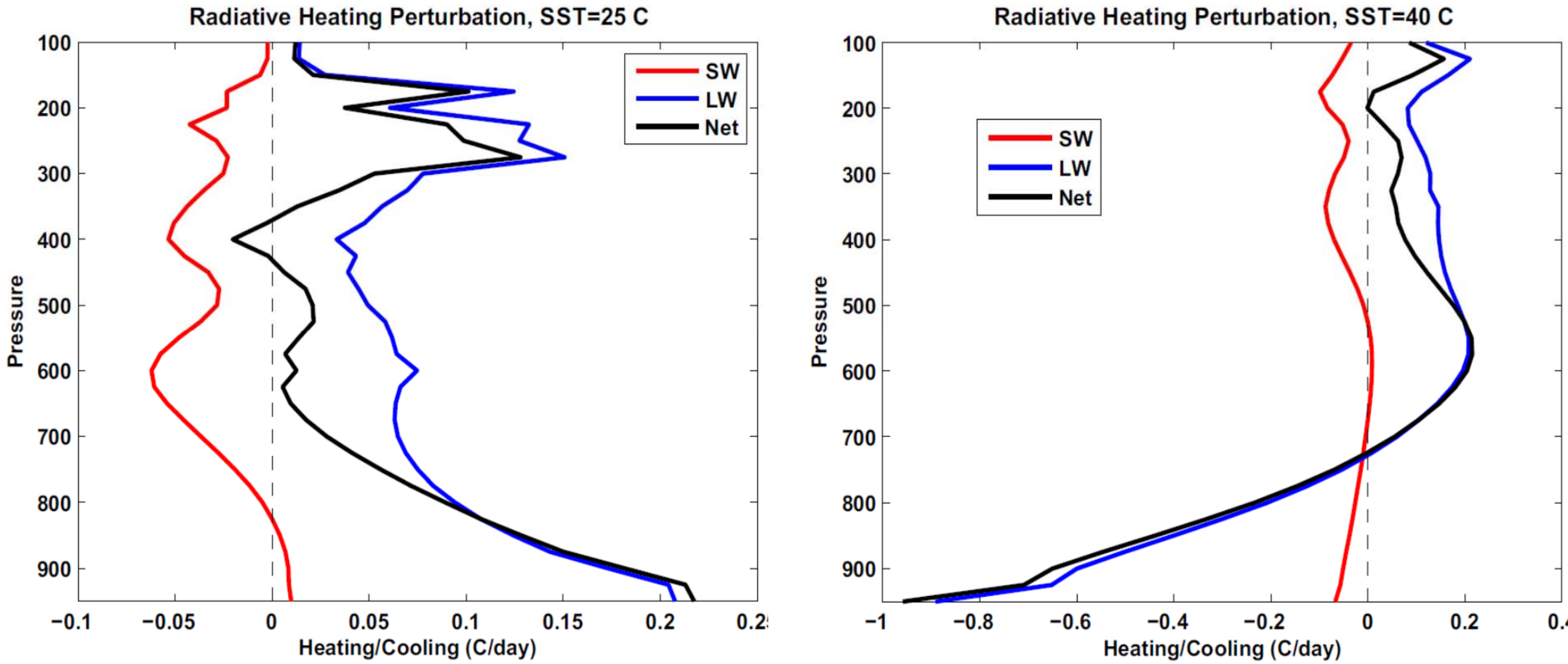
- No drift from RCE state when SST <~ 32 C

- Migration toward states with ascent or descent at higher SSTs

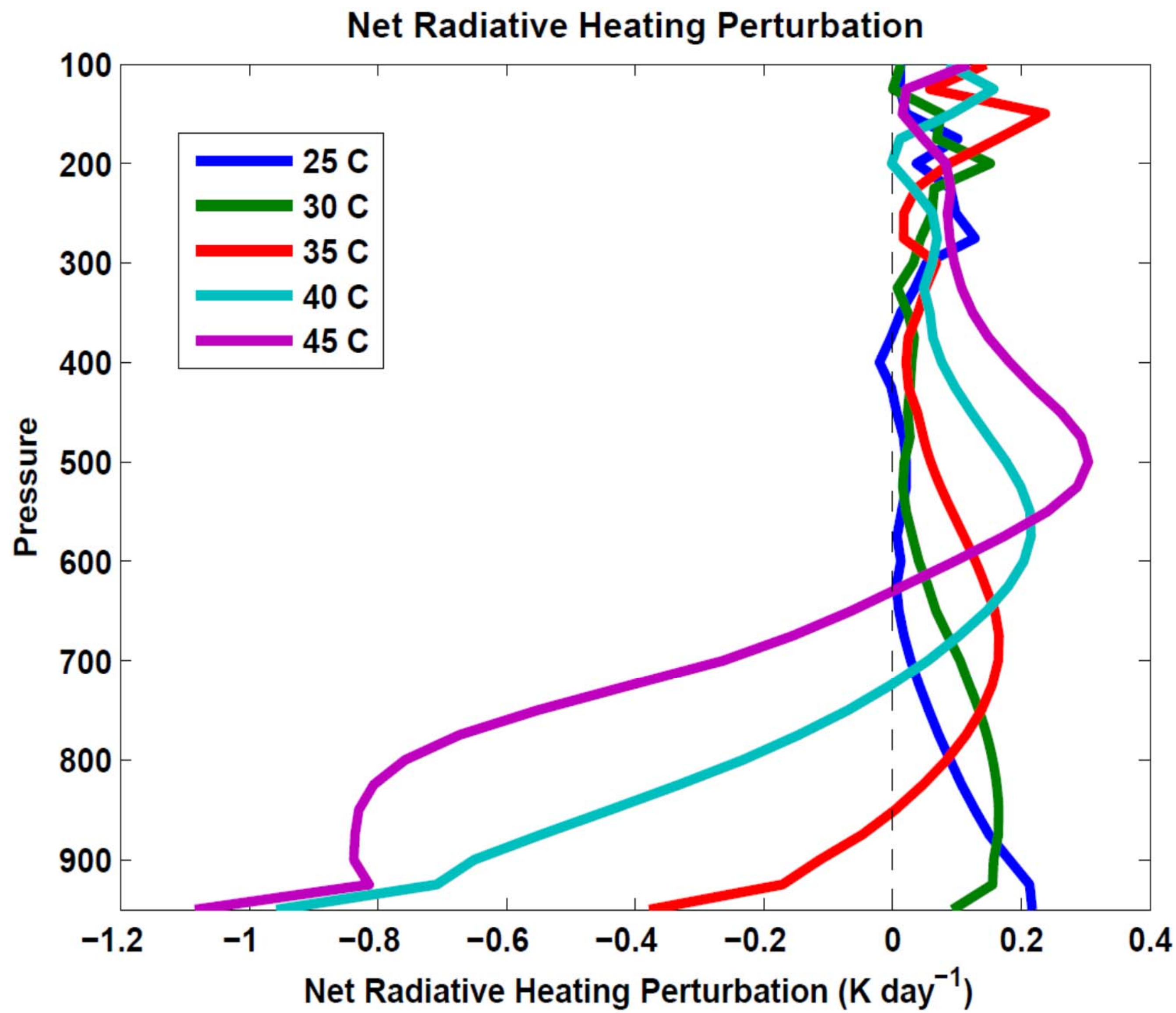
- These states correspond to multiple equilibria in two-column models by Raymond and Zeng (2000) and by several others since (e.g. Sobel et al., 2007; Sessions et al. 2010)



Specific Humidity (gm/Kg)
Omega (hPa hr^{-1})
Radiative Heating (K day^{-1})
Convective Heating (K day^{-1})
Pressure (mb)
Time (days)

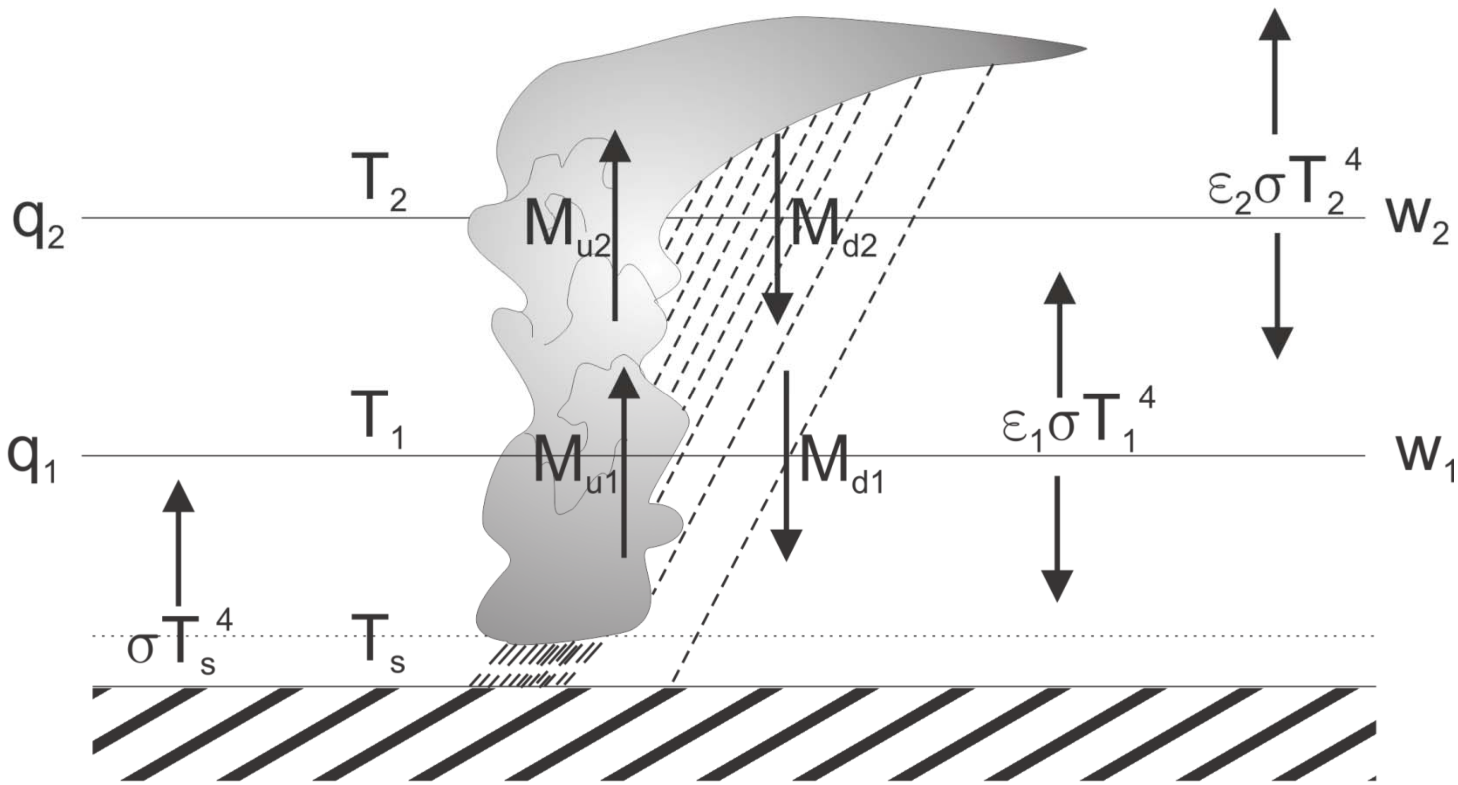


Perturbation shortwave (red), longwave (blue), and net (black) radiative heating rates in response to an instantaneous reduction of specific humidity of 20% from the RCE states for (left) SST525C and (right) 40C. Note the different scales on the abscissas.



Perturbation net radiative heating rates in response to an instantaneous reduction of specific humidity of 20% from the RCE states for SSTs ranging from 25 to 45C.

3. Two-Layer Model



Temperatures held constant, IR emissivities depend on q, convective mass fluxes calculated from boundary layer QE, w's calculated from WTG

Results of Linear Stability Analysis of Two-Layer Model:

Criterion for instability:

Dry static stabilities

emissivities

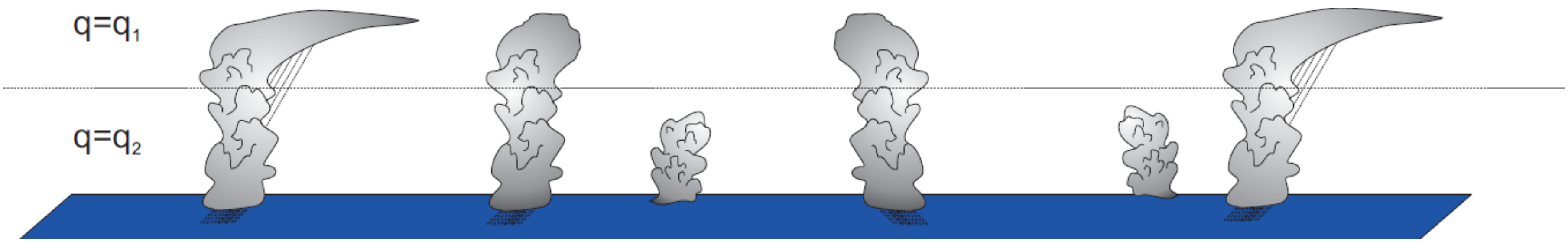
$$\frac{\overline{\dot{Q}}_1}{\varepsilon_1}\frac{\partial \varepsilon_1}{\partial q_1} + \left(1 - \varepsilon_p\right)\frac{\overline{\dot{Q}}_2}{\varepsilon_2}\frac{\partial \varepsilon_2}{\partial q_2} + \varepsilon_p \frac{\mathcal{S}_2}{\mathcal{S}_1}\frac{\sigma \varepsilon_1 T_2^4}{\rho_1}\frac{\partial \varepsilon_2}{\partial q_2} > 0.$$

Precipitation efficiency

- Radiative-convective equilibrium becomes linearly unstable when the infrared opacity of the lower troposphere becomes sufficiently large, and when precipitation efficiency is large

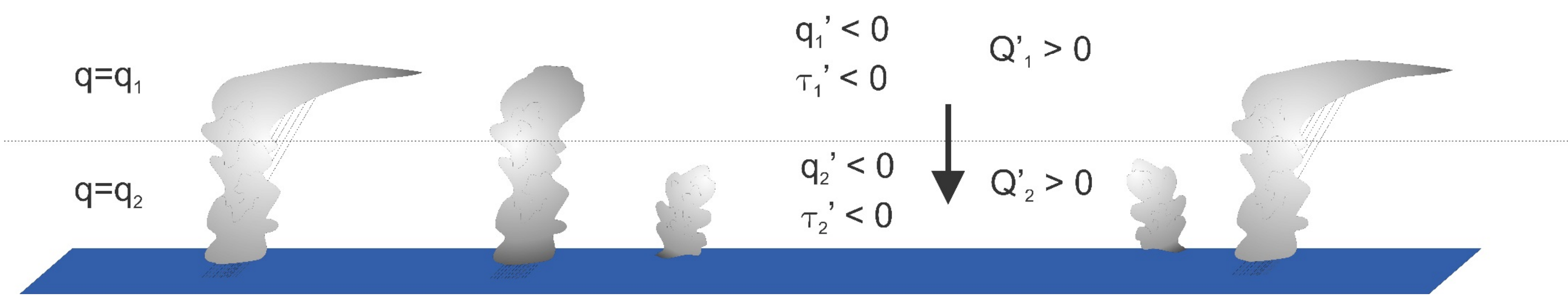
Interpretation

Ordinary Radiative-Convective Equilibrium

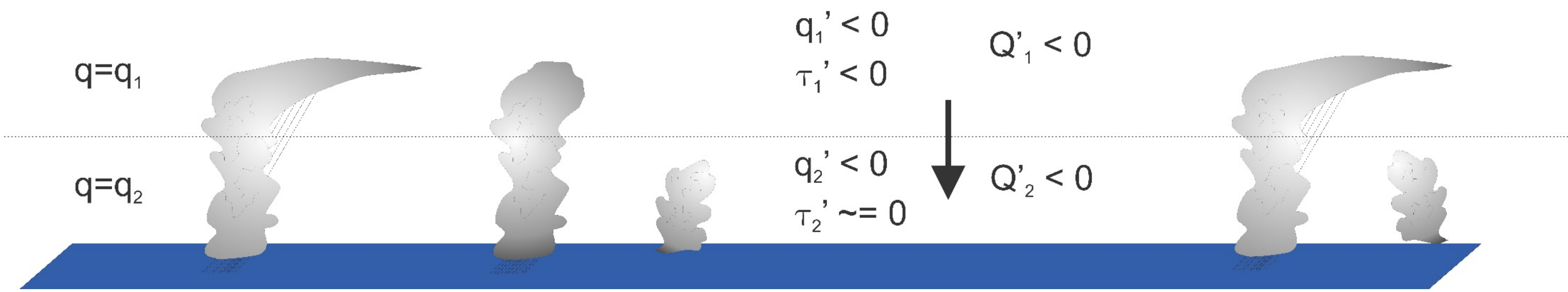


Introduce local downward vertical velocity

Low SST:
Little effect on shortwave radiative heating
Reduction of longwave radiative cooling throughout column
Some reduction in convective heating.
Net positive perturbation heating
Large scale ascent: Negative feedback



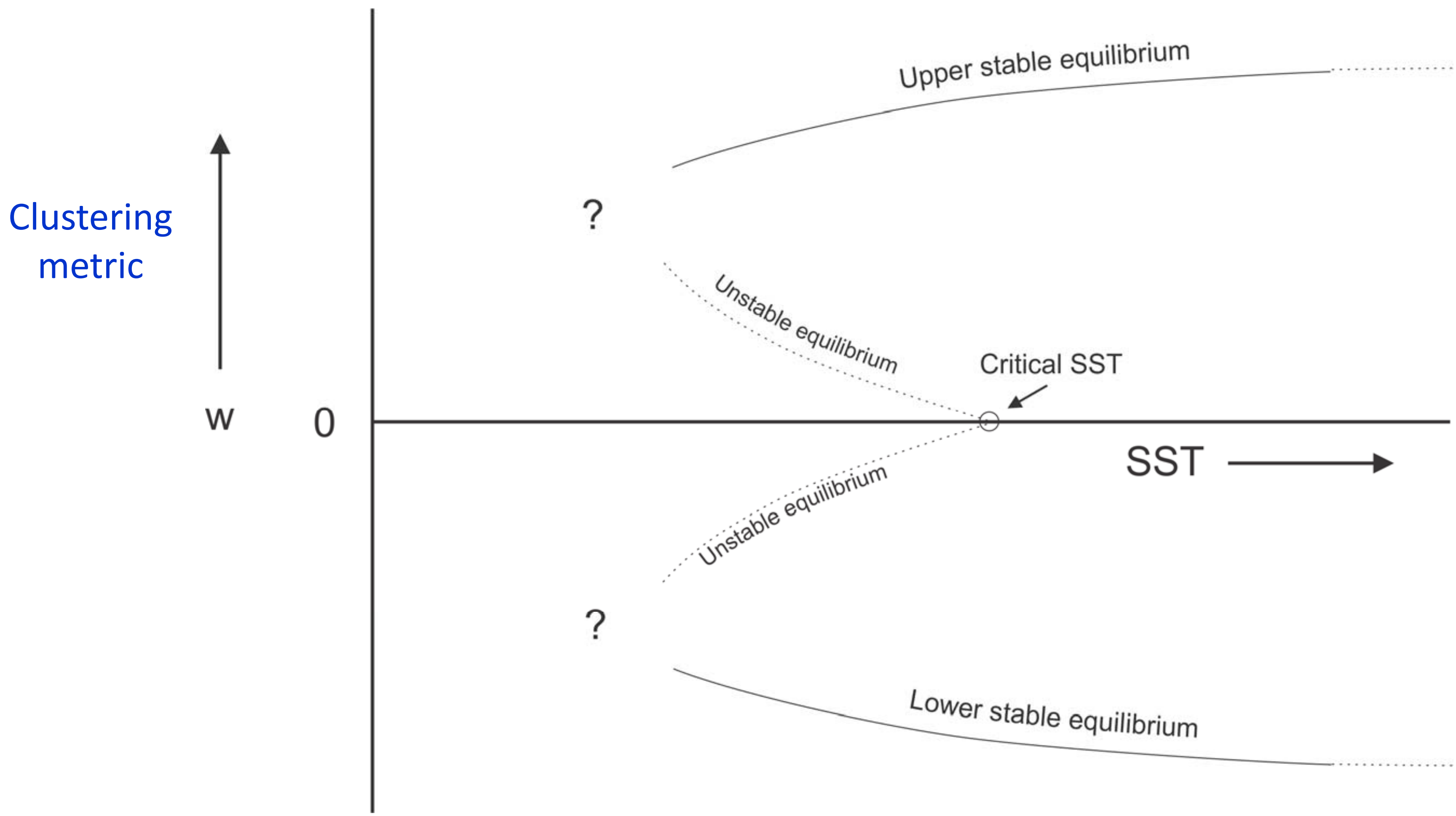
High SST:
Strong negative perturbations of shortwave heating
Reduction of longwave radiative cooling in upper troposphere
Increased longwave cooling of lower troposphere
Decreased convective heating
Net negative perturbation radiative heating
Large scale descent: **Positive feedback**



Note:

Once cluster forms, it is strongly maintained by intense negative OLR anomaly associated with central dense overcast. But cloud feedbacks are NOT important in instigating the instability. This leads to strong hysteresis in the radiative-convective system

Hypothesized Subcritical Bifurcation

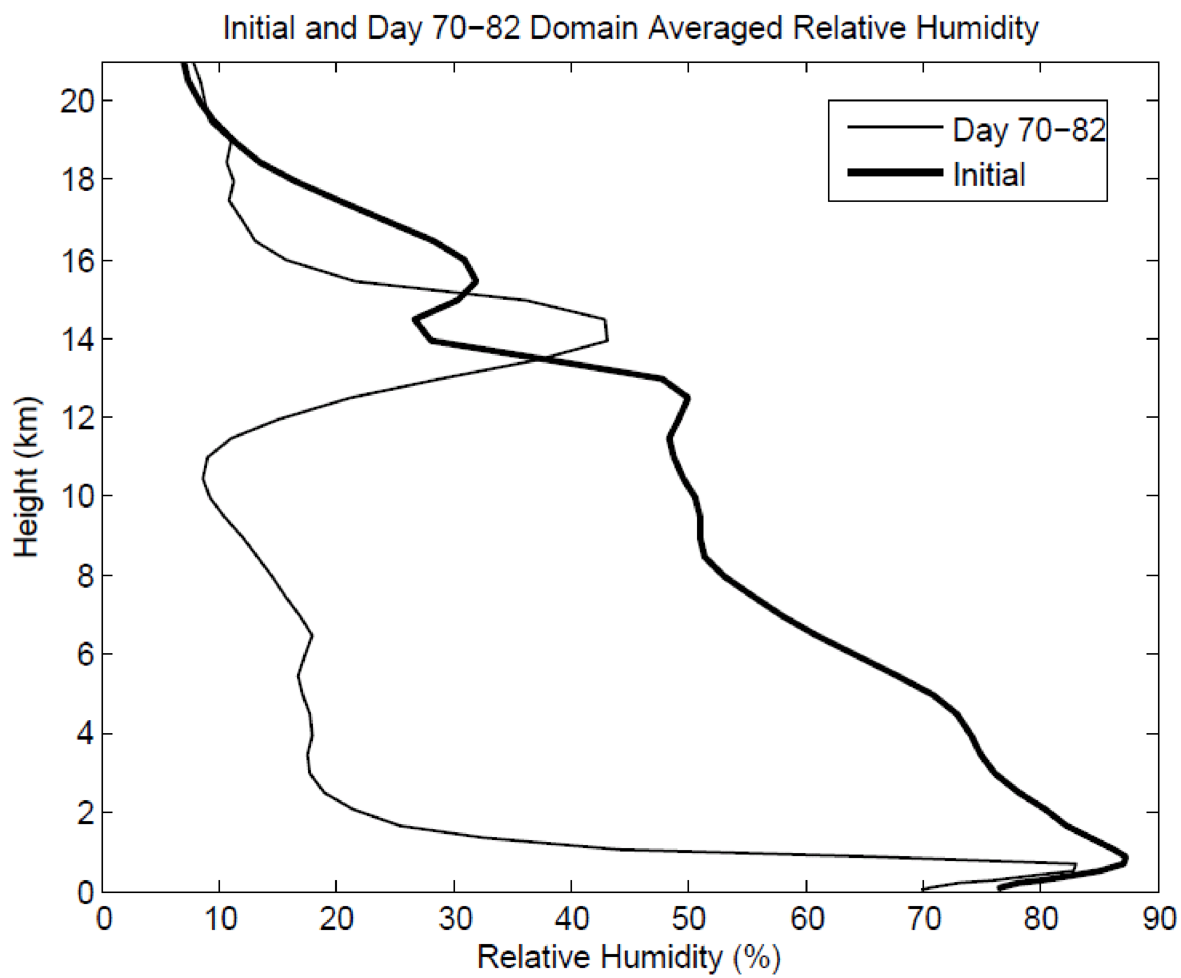


Summary

- Radiative-Convective Equilibrium remains an interesting problem in climate science
- At high temperature, RCE is unstable, owing to the particular dependencies of convection and radiation on atmospheric water vapor and clouds
- Aggregation of convection may have profound effects on climate
- Physics of aggregation may not operate well, if at all, in today's climate models

Consequences

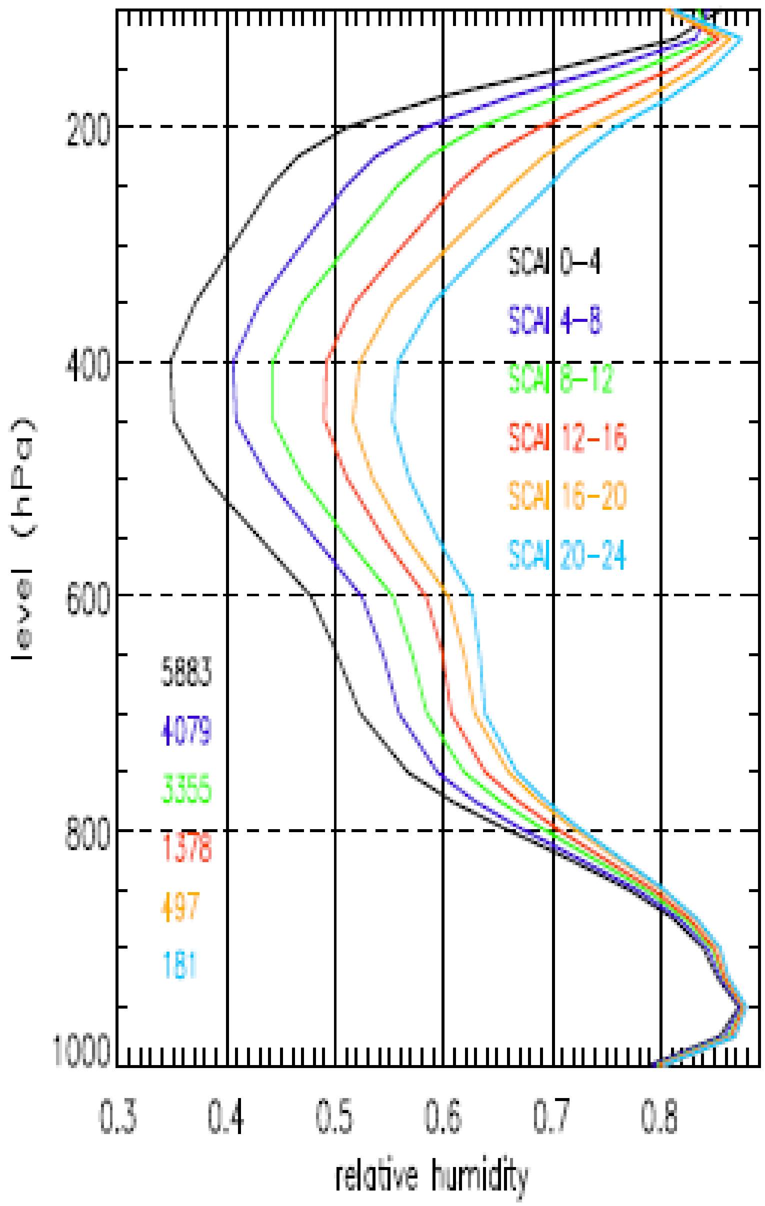
Aggregation Dramatically Dries Atmosphere!



Variation of tropical relative humidity profiles with a Simple Convective Aggregation Index (SCAI).

Courtesy Isabelle Tobin, Sandrine Bony, and Remy Roca

Tobin, Bony, and Roca, *J. Climate*, 2012



Hypothesis

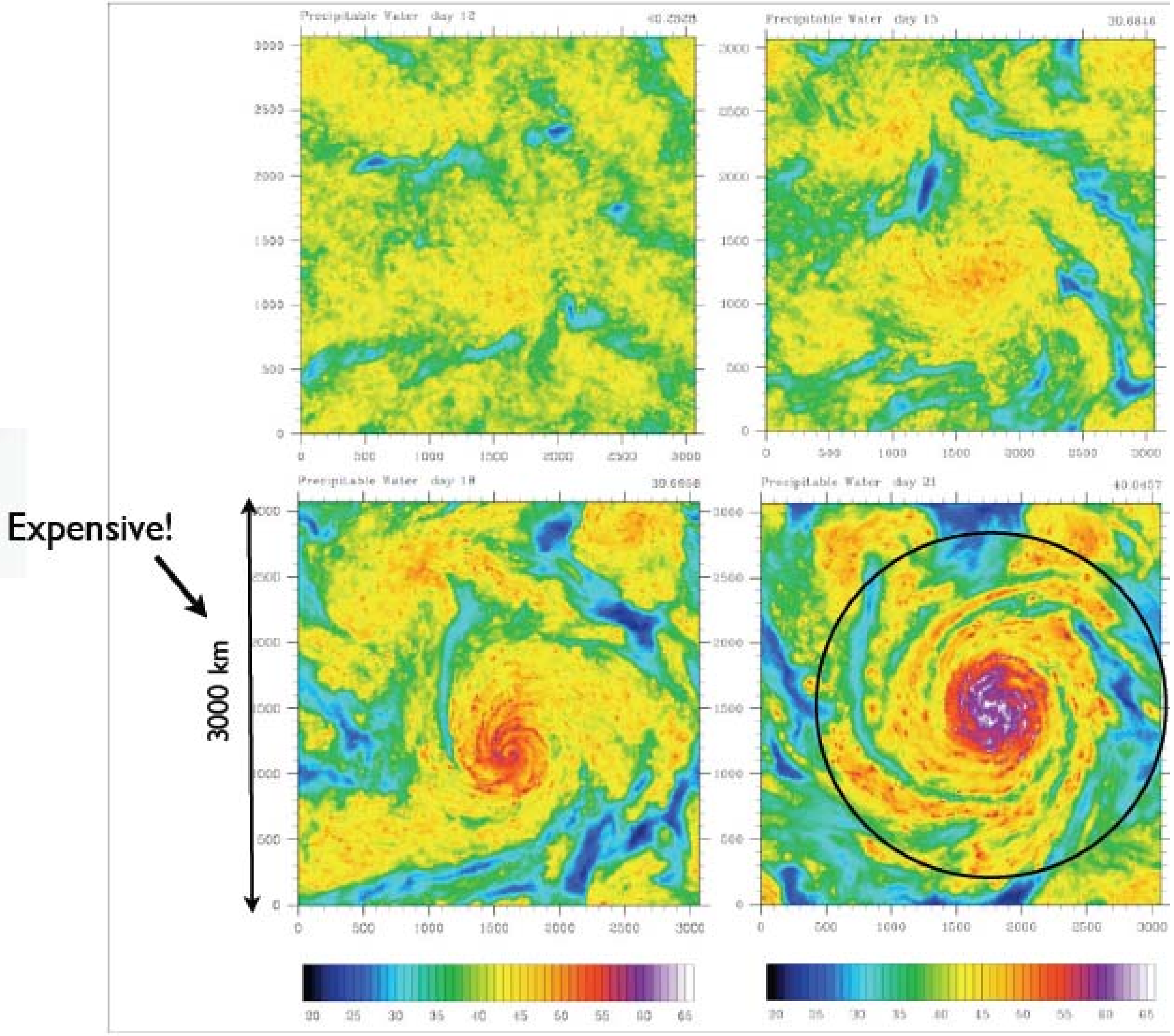
- At high temperature, convection self-aggregates
- →Horizontally averaged humidity drops dramatically
- →Reduced greenhouse effect cools system
- →Convection disaggregates
- →Humidity increases, system warms
- →System wants to be near phase transition to aggregated state

Recipe for Self-Organized Criticality
(First proposed by David Neelin, but by different mechanism)

- System should reside near critical threshold for self-aggregation: Regulation of tropical sea surface temperature!

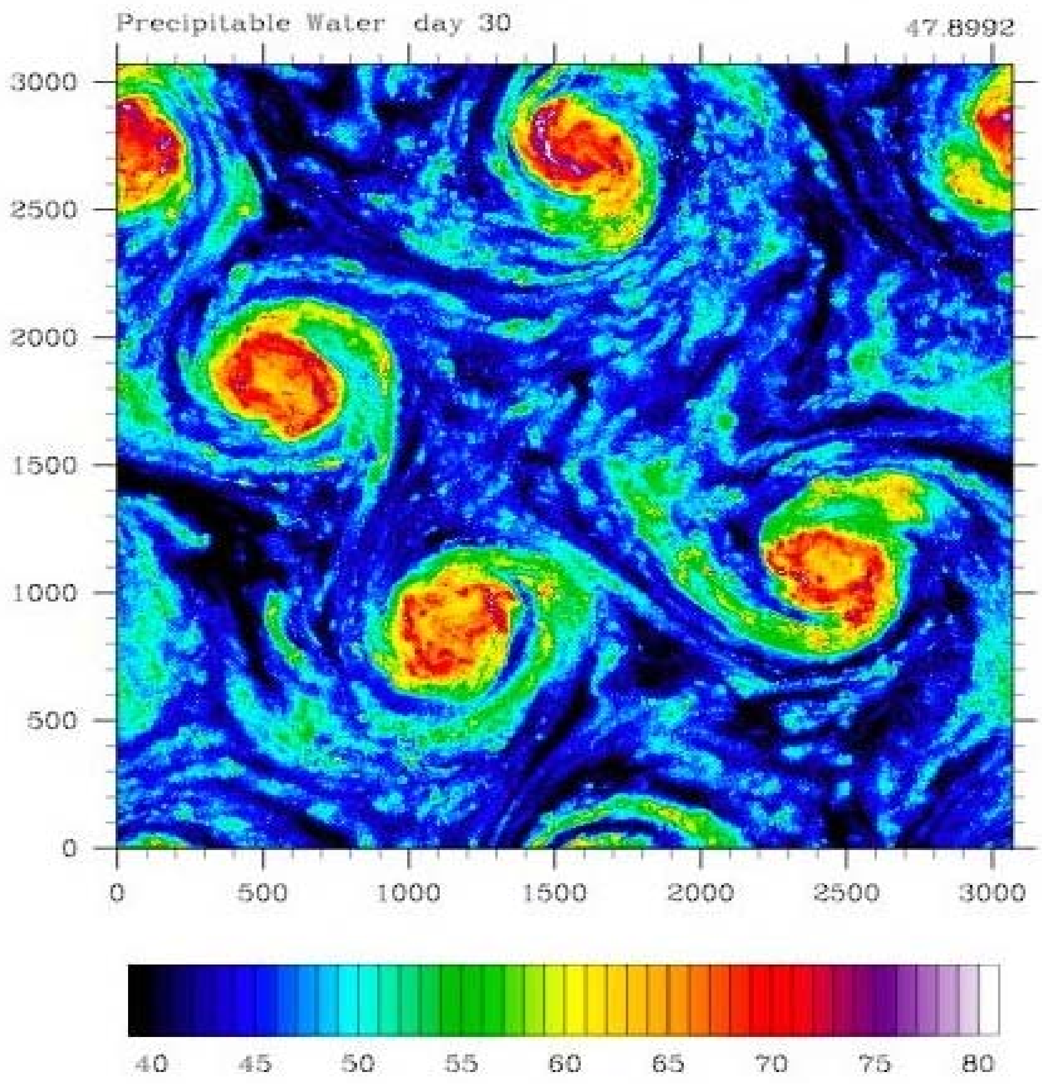
- Convective cluster size should follow power law distribution

Self-Aggregation on an f-plane




Vincent Van Gogh: Starry Night

Self-Aggregation on an f-plane

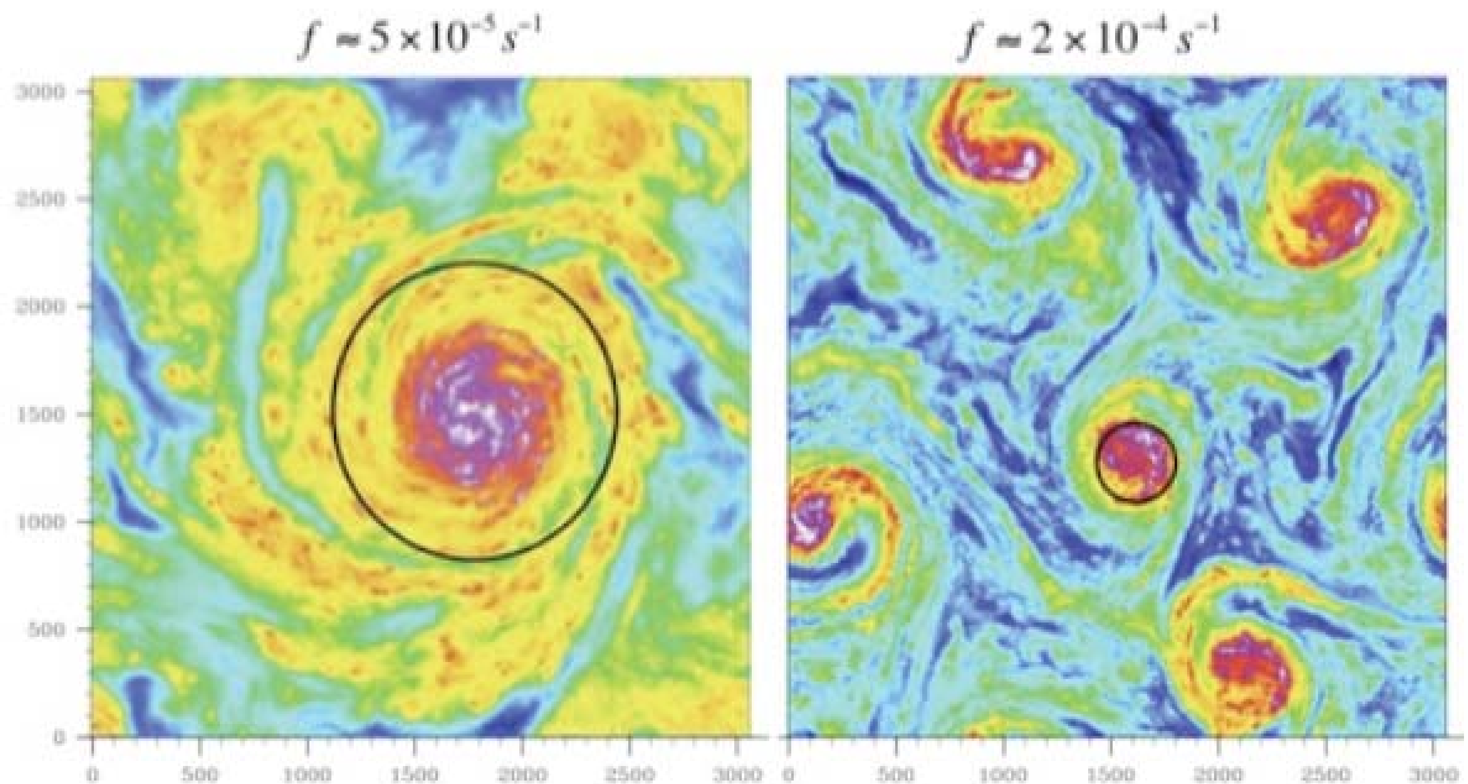


Hurricane-World Scaling

- Modified thermodynamic efficiency: $\varepsilon \equiv \frac{T_s - T_o}{T_o}$
- Angular velocity of earth's rotation: Ω
- Saturation water concentration of sea surface: $q_s \sim e^{T_s}$
- Net top-of-atmosphere upward radiative flux: F_{TOA}
- Net upward surface radiative flux: F_s
- Potential intensity: $V_p^3 \approx \frac{\varepsilon\left(F_{TOA} - F_s\right)}{C_D}$

Hurricane-World Scaling

- Radius of maximum winds: $$r_m \sim \frac{V_{pot}}{\Omega}$$
- Distance between storm centers: $$D \sim \frac{\sqrt{L_v q_s}}{\Omega}$$
- Number density: $$n \sim \frac{\Omega^2}{L_v q_s}$$


$f \approx 5 \times 10^{-5}\, s^{-1}$
$f \approx 2 \times 10^{-4}\, s^{-1}$
0
500
1000
1500
2000
2500
3000

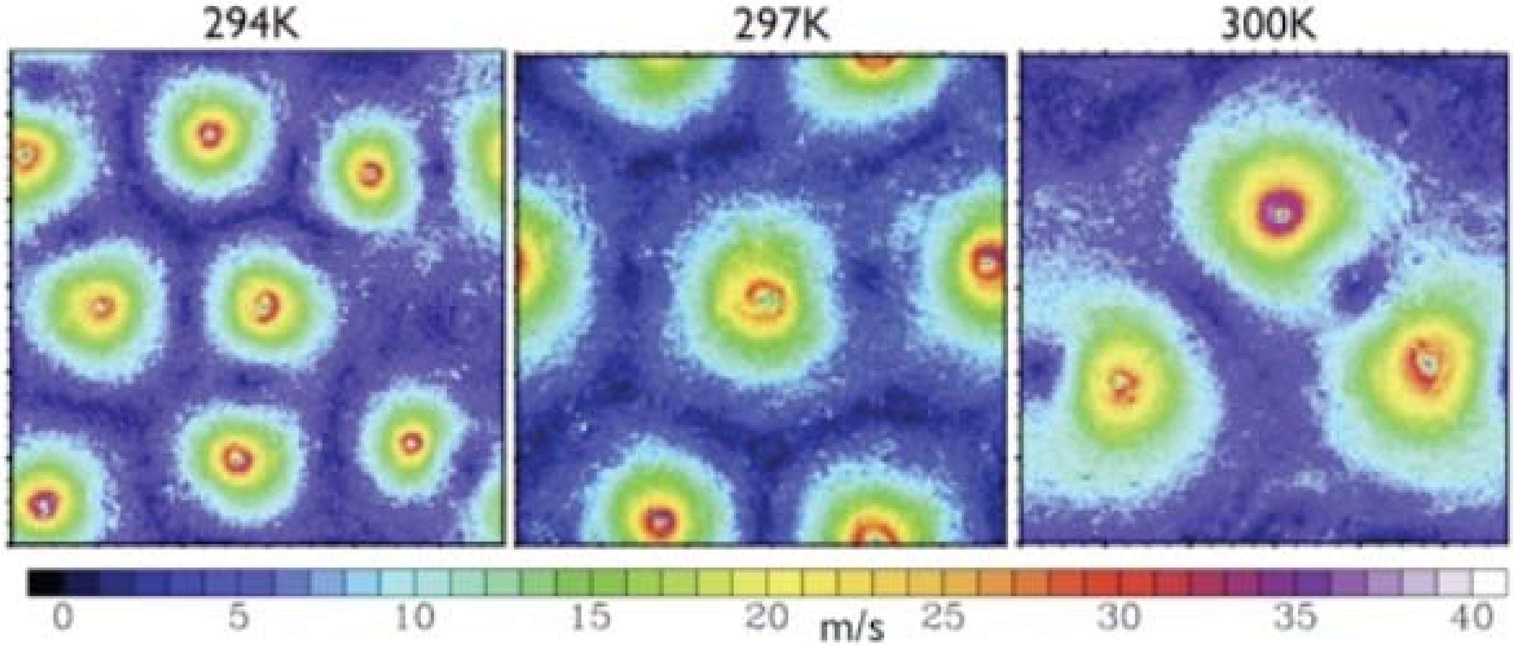


Figure 2 Snapshots of near-surface wind (in m/s) in RCE with rotation for three different values of the SST.