

Radiative-Convective Equilibrium over Islands

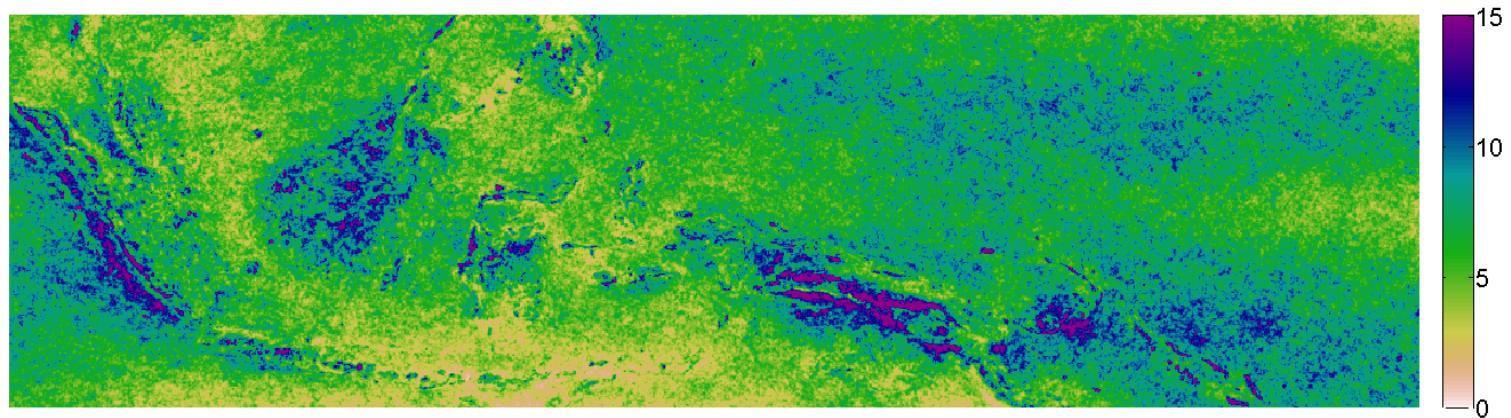
Tim Cronin

NOAA/HUCE postdoctoral fellow

Caltech Monsoons Workshop, 5/21/2015

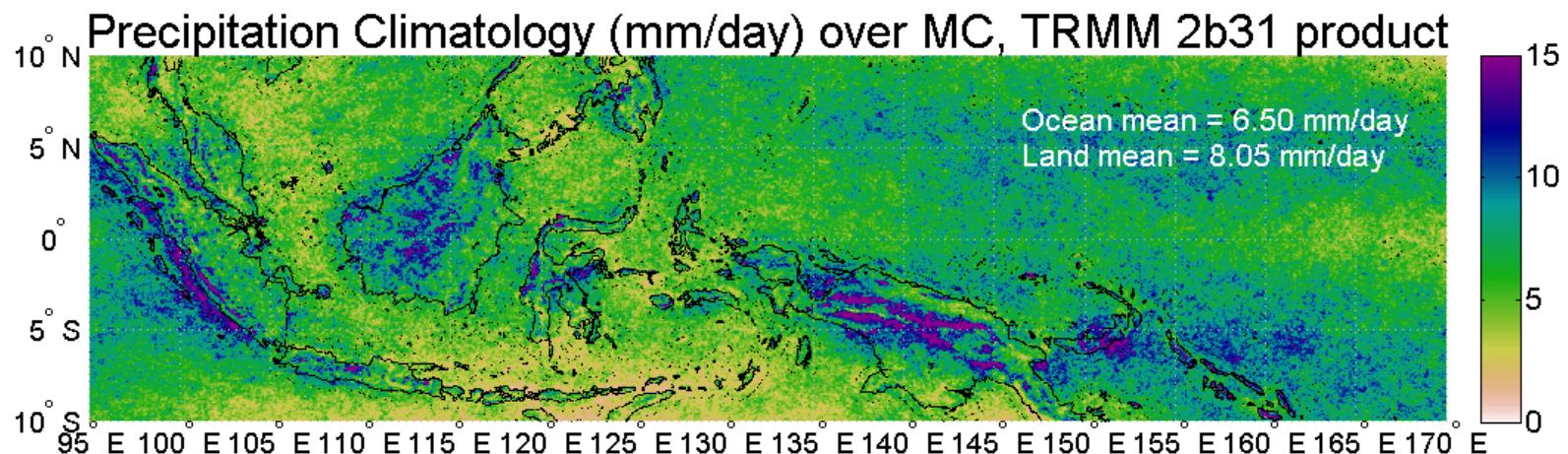
collaborators: Kerry Emanuel, Peter Molnar

Why do we care about island rainfall?

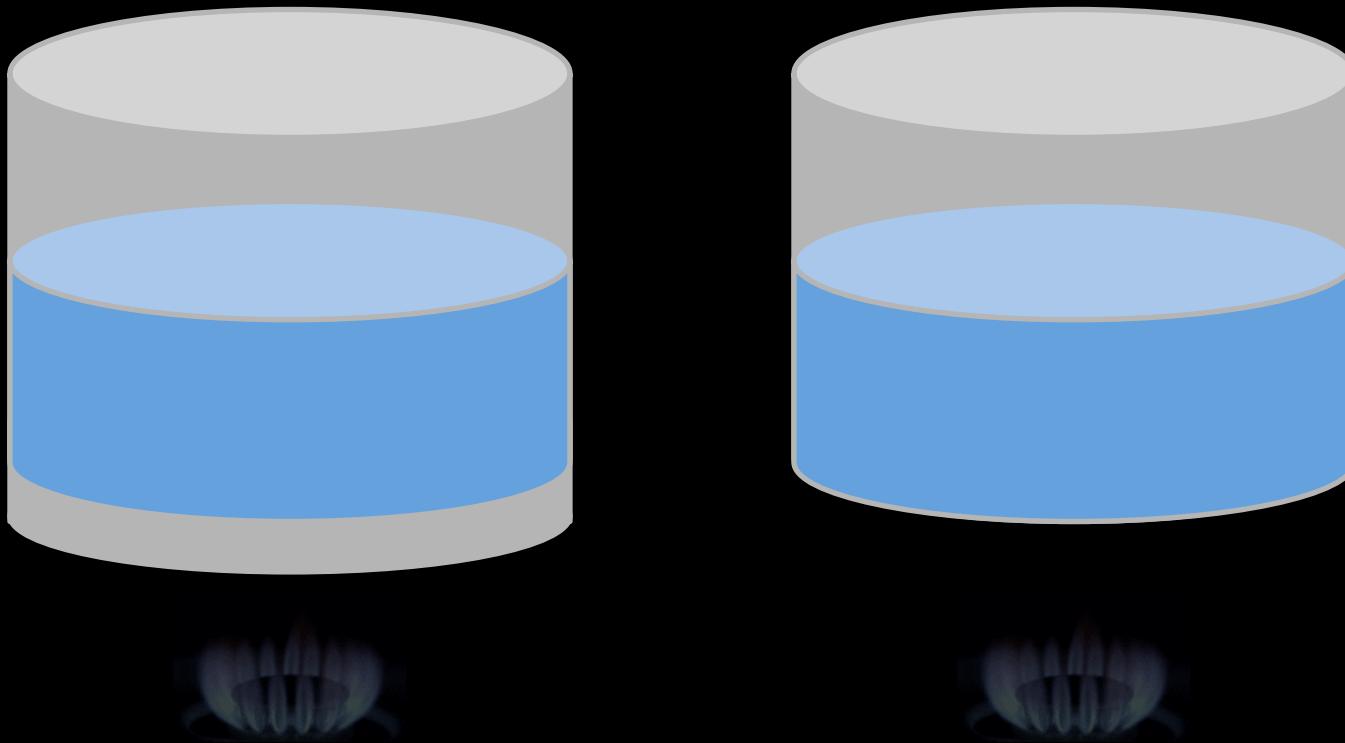


Islands are Rainier than Nearby Ocean

- As-Syakur *et al.* (2013):
 - island average = 7.62 mm/day
 - ocean average = 5.47 mm/day



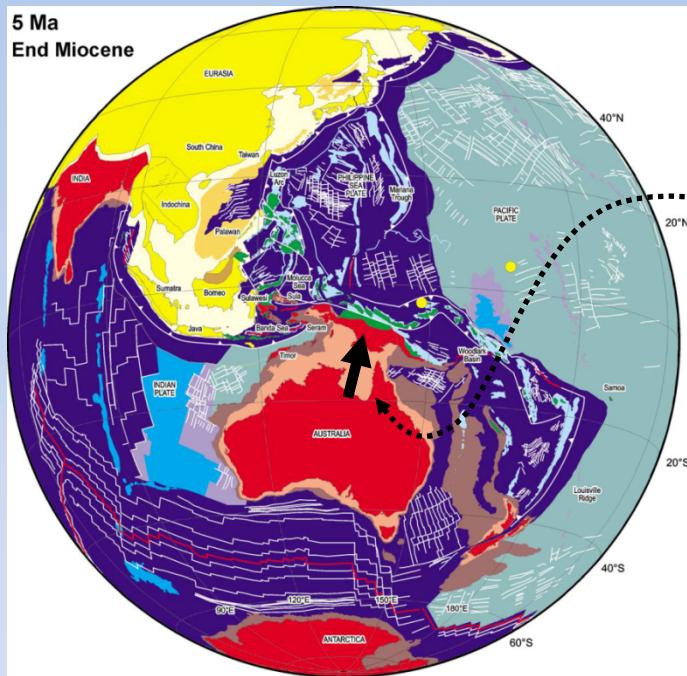
Does the Diurnal Cycle “Rectify”?



An analogy:

- boiling two pots of water with an oscillating heat source (like the sun)
- one pot has a thicker bottom/higher heat capacity (like the ocean)
- do the two pots boil a different amount of water? (like the land/ocean precipitation contrast)

Why do we care about island rainfall?

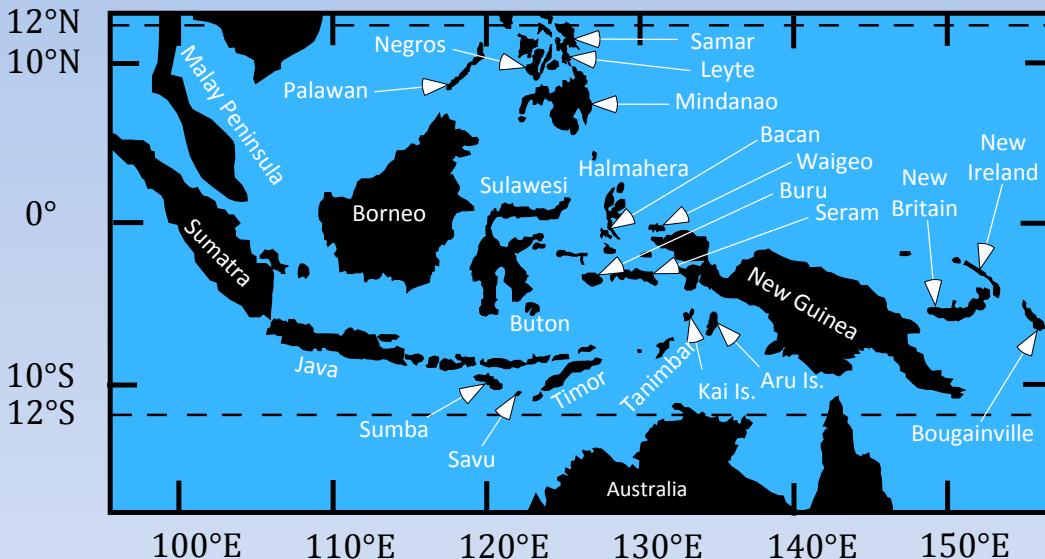


0.5-1 degree
north per million
years

- Does island rainfall enhancement have implications for the large-scale circulation in the tropics?

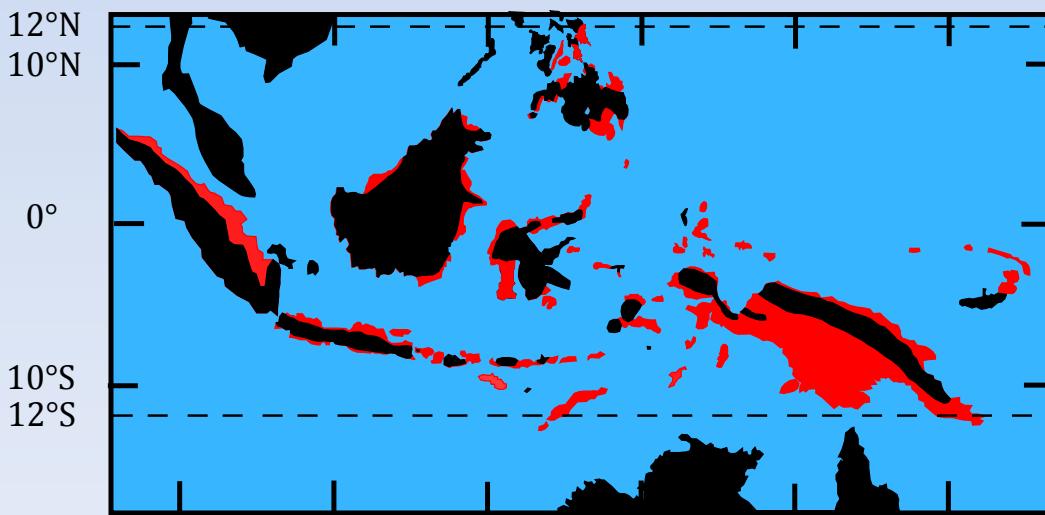
Figure from: Hall (2002), *Journal of Asian Earth Sciences*

(Is)land area has expanded in past 5 Ma

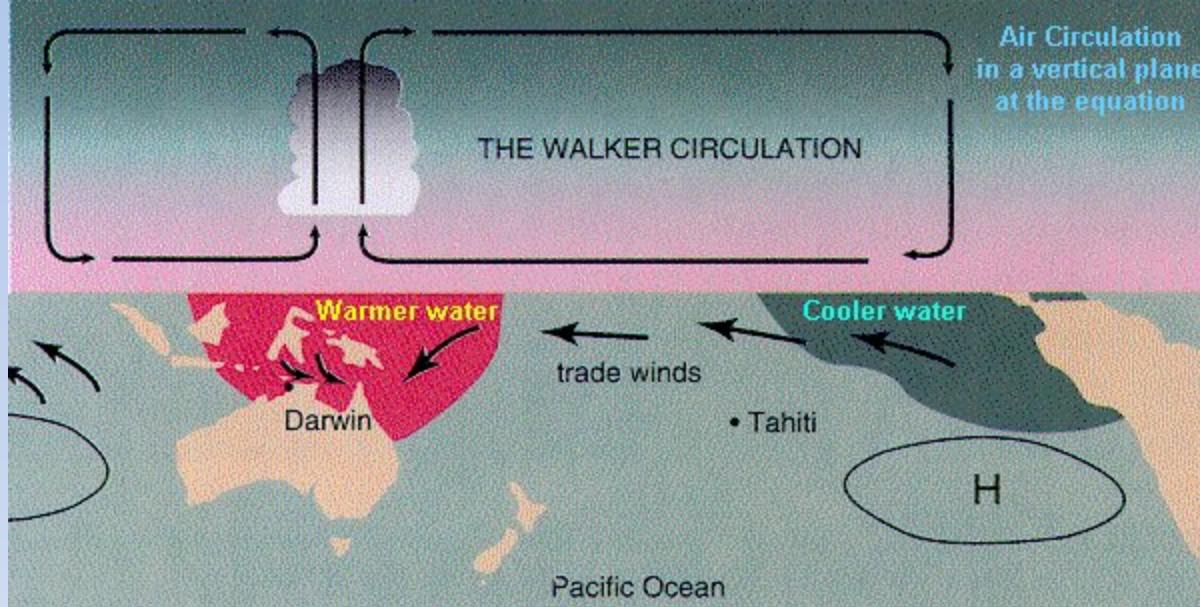


- Today: land area 12 S-12N is 3.1 million km²
- 5 Ma: land area 12 S-12N ~1.9 million km²
- ~60% areal increase

[Molnar and Cronin, 2015,
Paleoceanography]

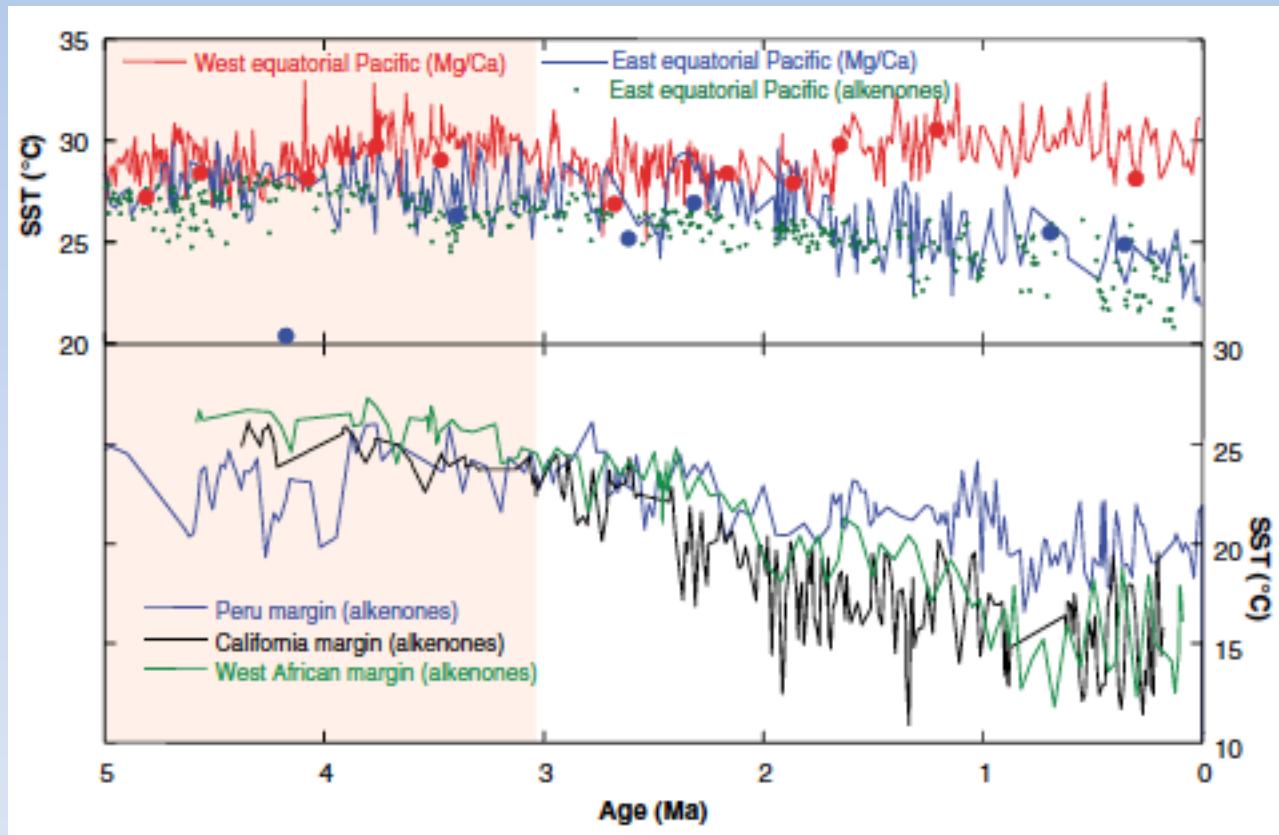


The Walker Circulation



- Walker Circulation variability correlates more strongly with rainfall over the islands than with rainfall over the “warm pool” (*Dayem et al., 2007*)

Pliocene: Less Island Area, Weaker Equatorial Pacific SST gradient



- 3-5 Ma: much smaller temperature difference between East and West Pacific (*Fedorov et al., 2006*)

Radiative-Convective Equilibrium (RCE)

- The simplest climate model: assumes energy balance in the absence of lateral heat transport
- 1) Atmosphere-only RCE: Convective heating balanced by radiative cooling to space
 - 2) Climate RCE: Atmospheric RCE plus requirement of surface energy balance (or top-of-atmosphere energy balance)

Surface Heat Capacity Defines Island

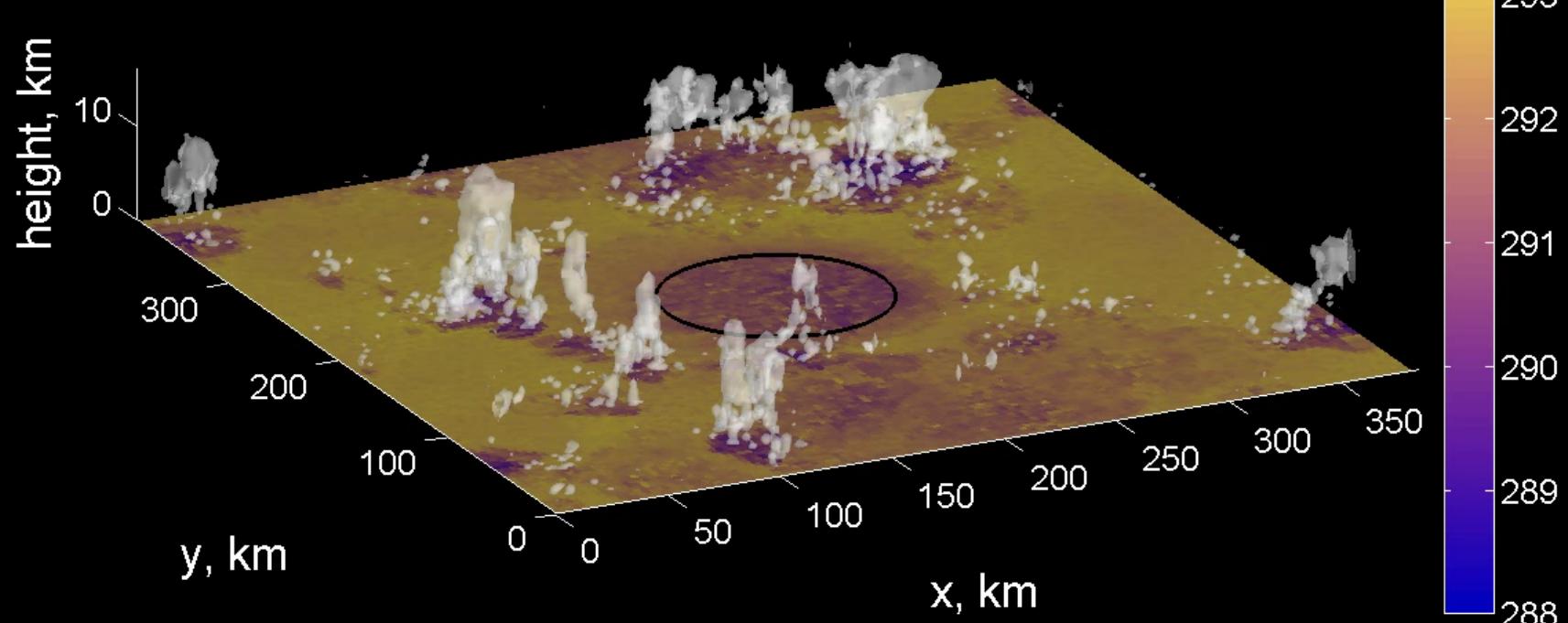
- Simulate radiative-convective equilibrium (RCE), with time-varying insolation
- Allow surface temperatures to be interactive:

$$C_S \frac{\partial T_S}{\partial t} = Q_S - Q_L - H - E$$

Surface Heat Capacity:
Large difference between
land and ocean

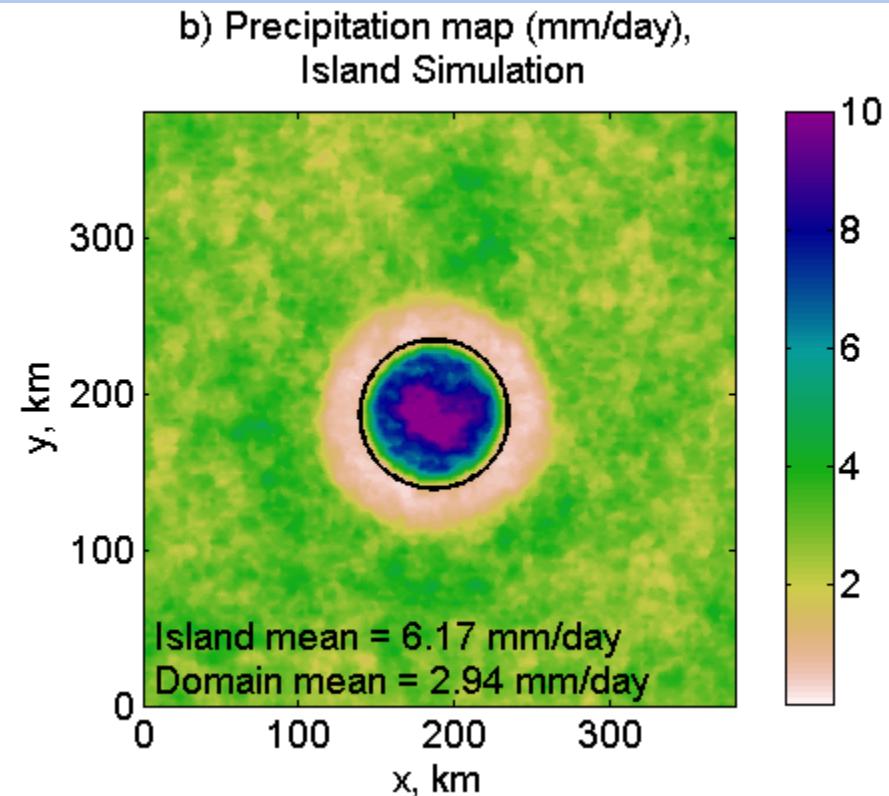
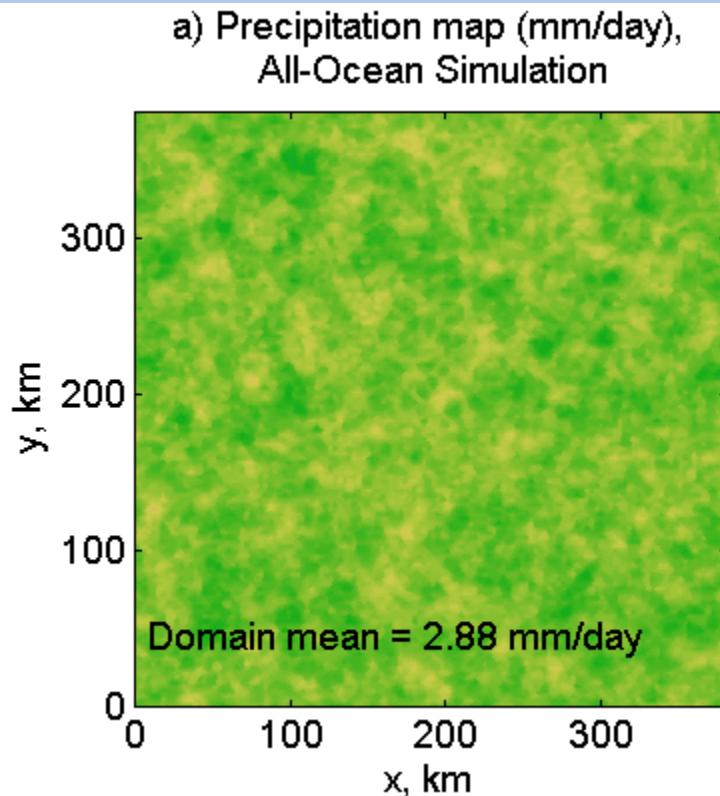
My choices of C_S :
5-cm water equivalent for
land
1-meter water equivalent
for ocean

Isosurface of Condensate=0.3g/kg and Surface Air T (K)
Day 330, Local Solar Time : 00:00



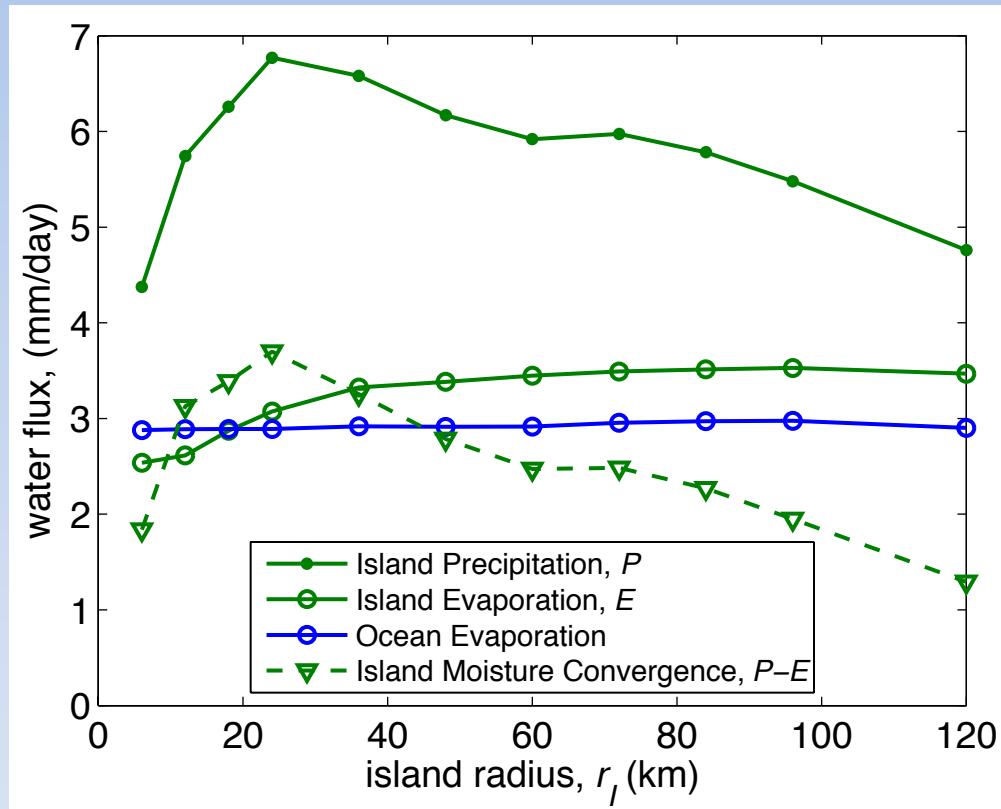
Note: Vertical Scale Stretched $\times 4$ Relative to Horizontal Scale
Island Outlined by Black Circle

Mean Rainfall Rate



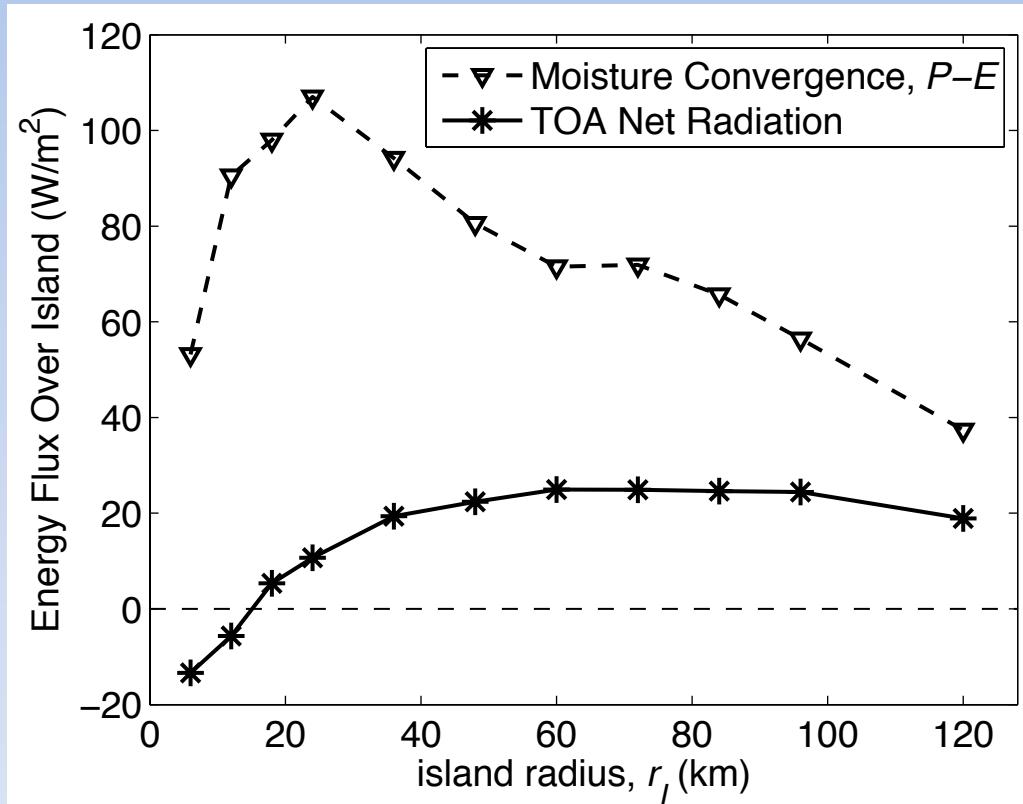
- How does this rainfall enhancement depend on island size?
- What are the mechanisms for rainfall enhancement?

Mean Rainfall vs. Island Size



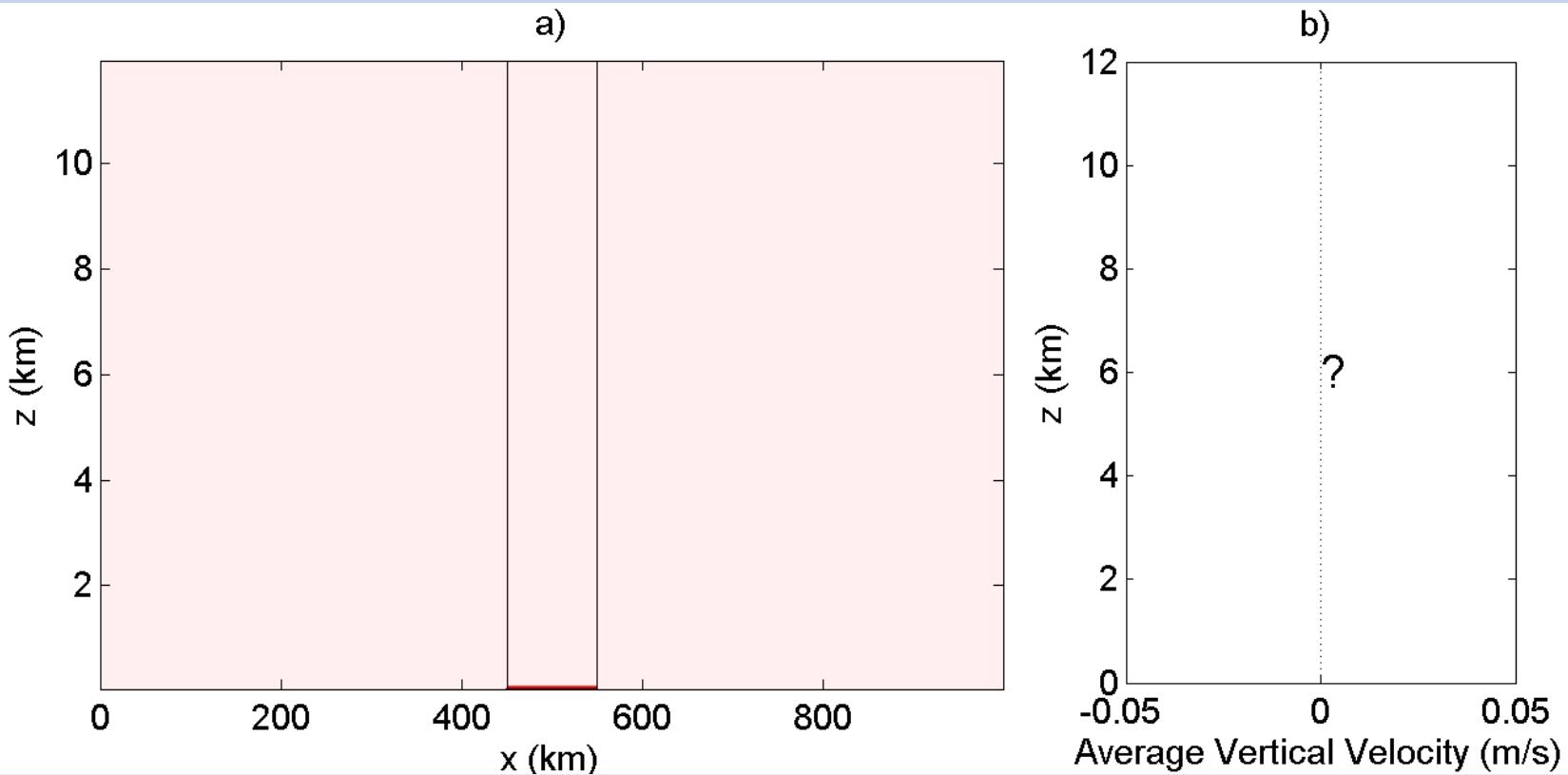
- Atmospheric moisture convergence over the island depends strongly on island size
- Evaporation over island generally exceeds evaporation over ocean

Moisture Convergence vs. Energy Balance

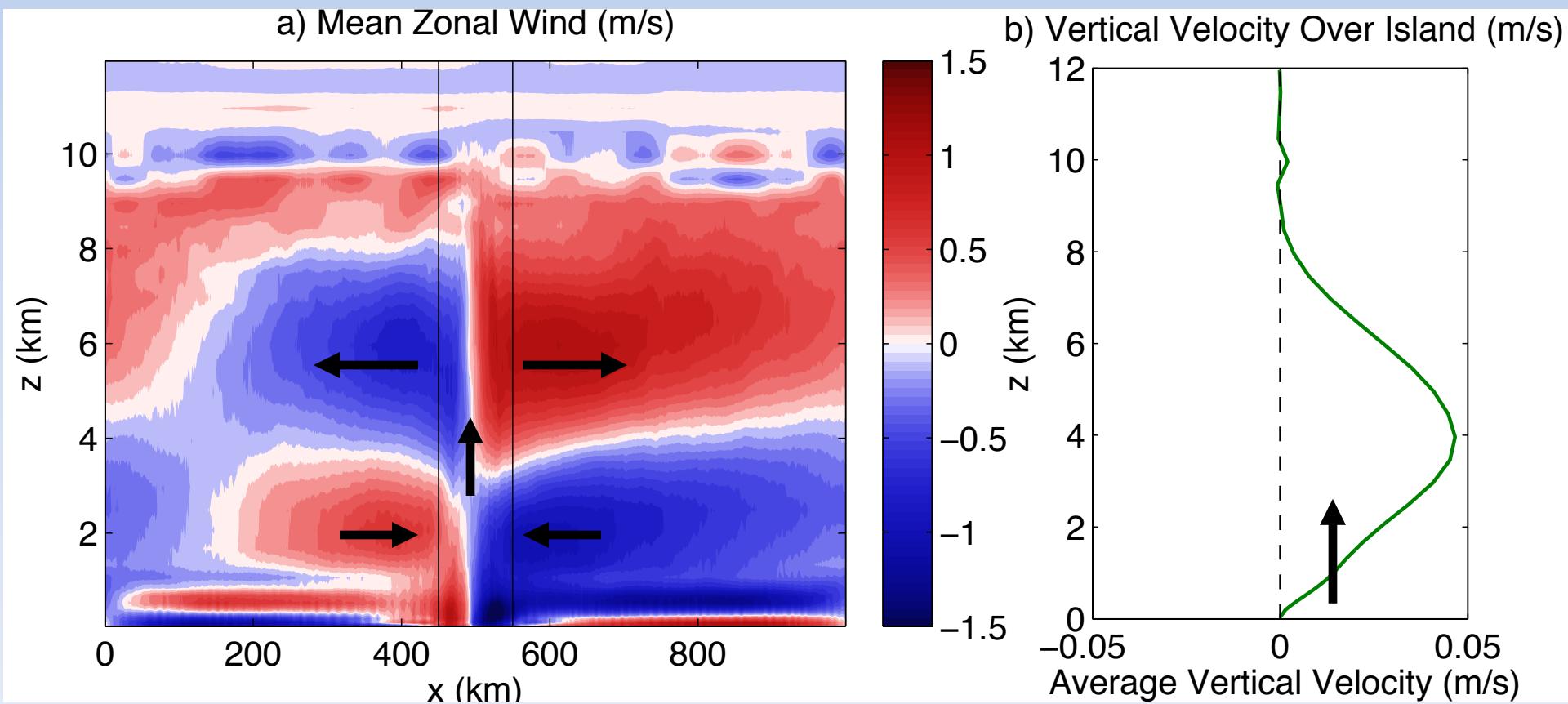


- Atmospheric moisture convergence: not correlated with top-of-atmosphere energy flux
- Why not? Circulation is complicated and time-varying.

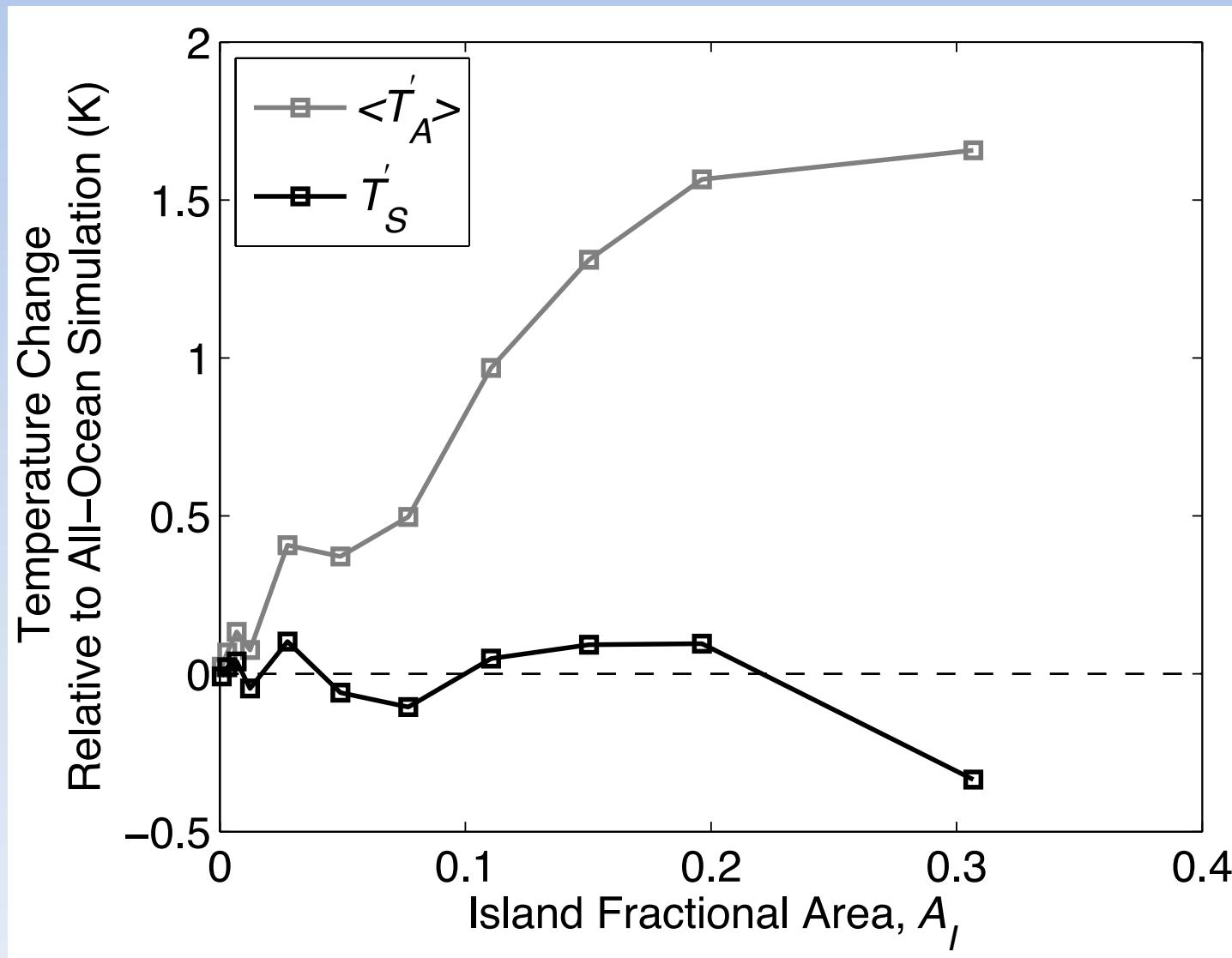
Dynamical Rectification from an Oscillating Heat Source?



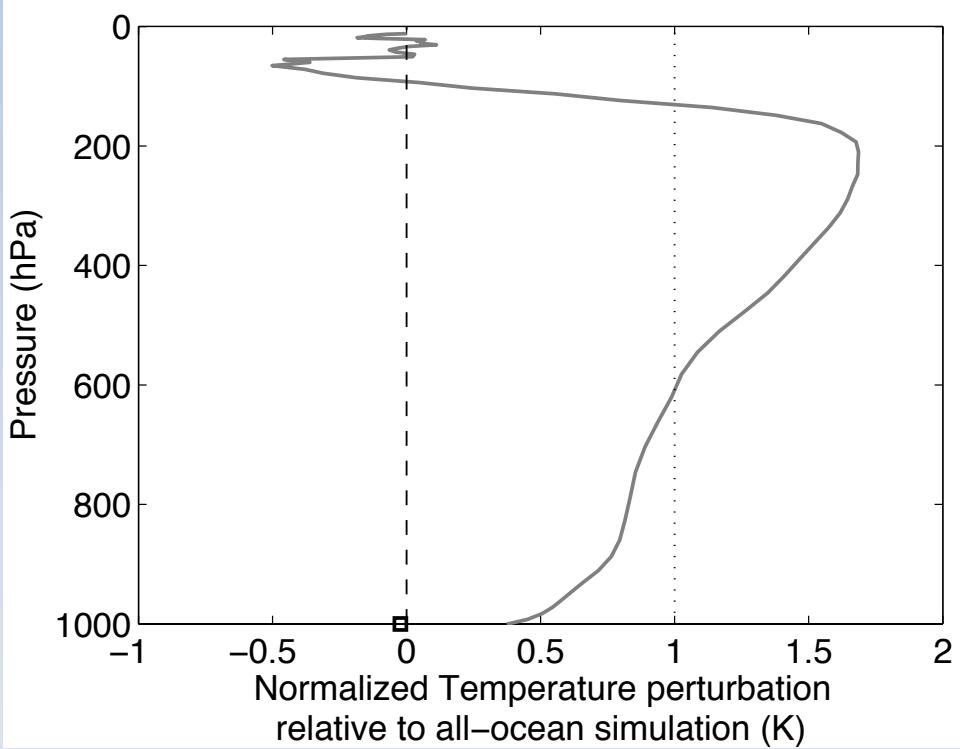
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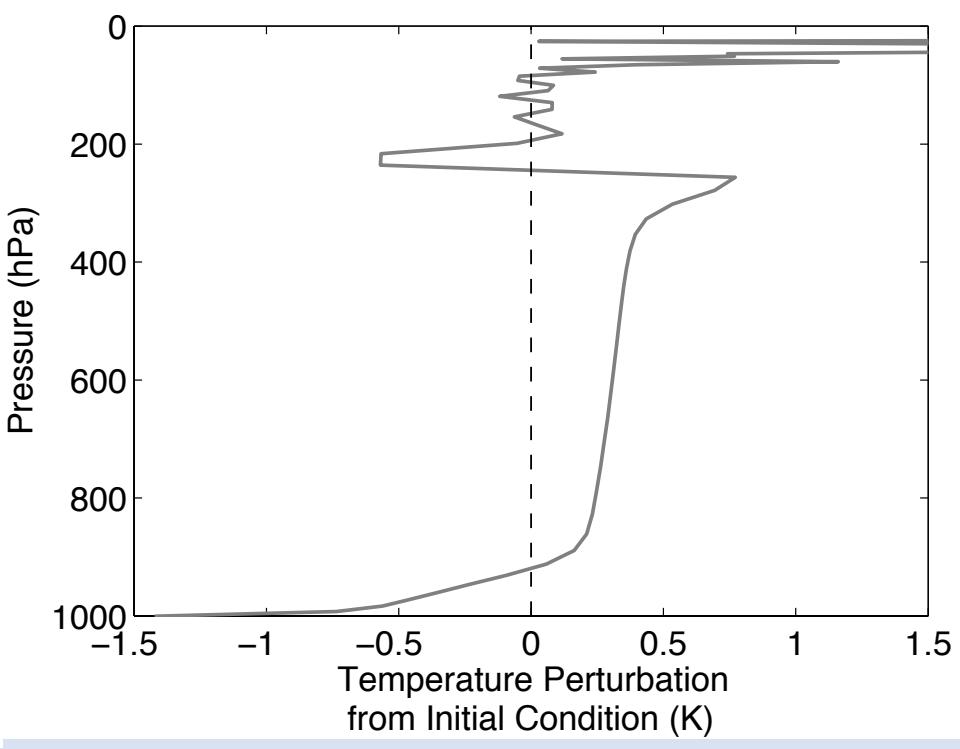
Domain-mean Tropospheric Warming



Domain-mean Warming Structure

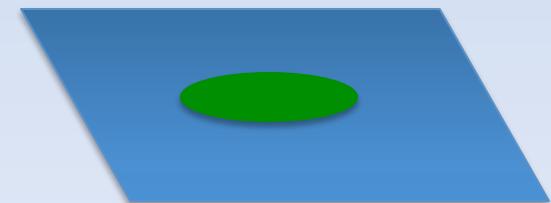
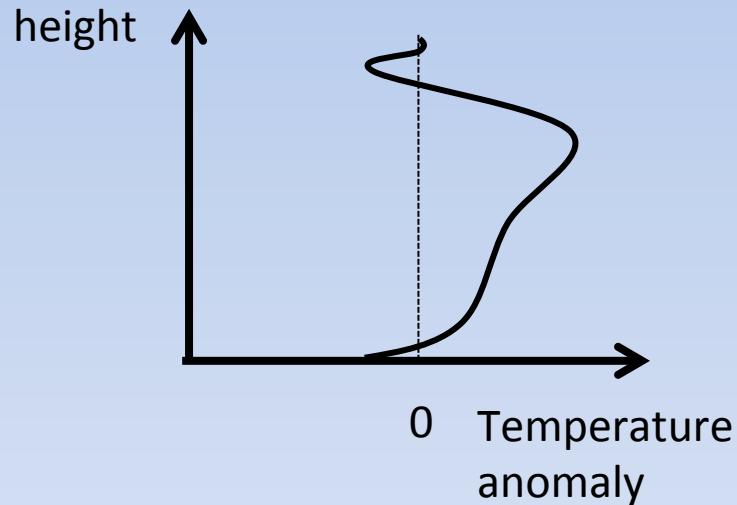


Full Simulations

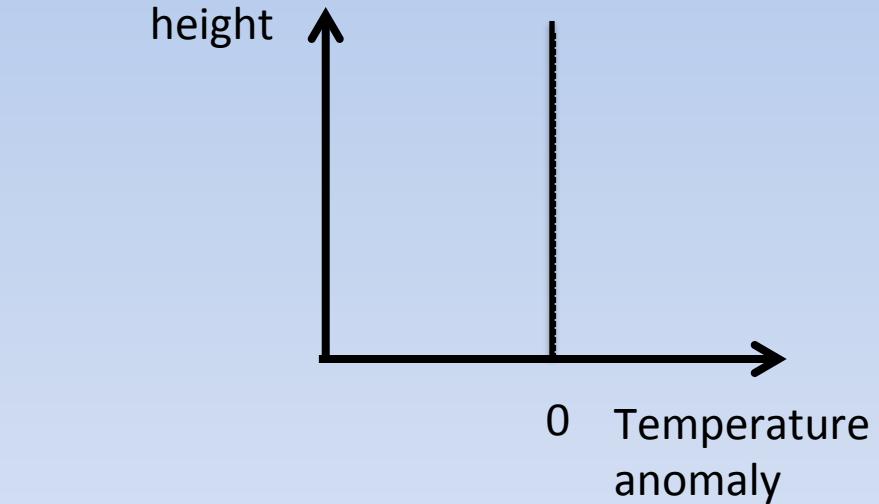


2D dry example with
oscillating heat source

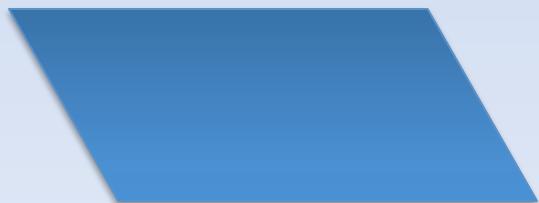
Domain-mean warming and circulation



Region with island(s)

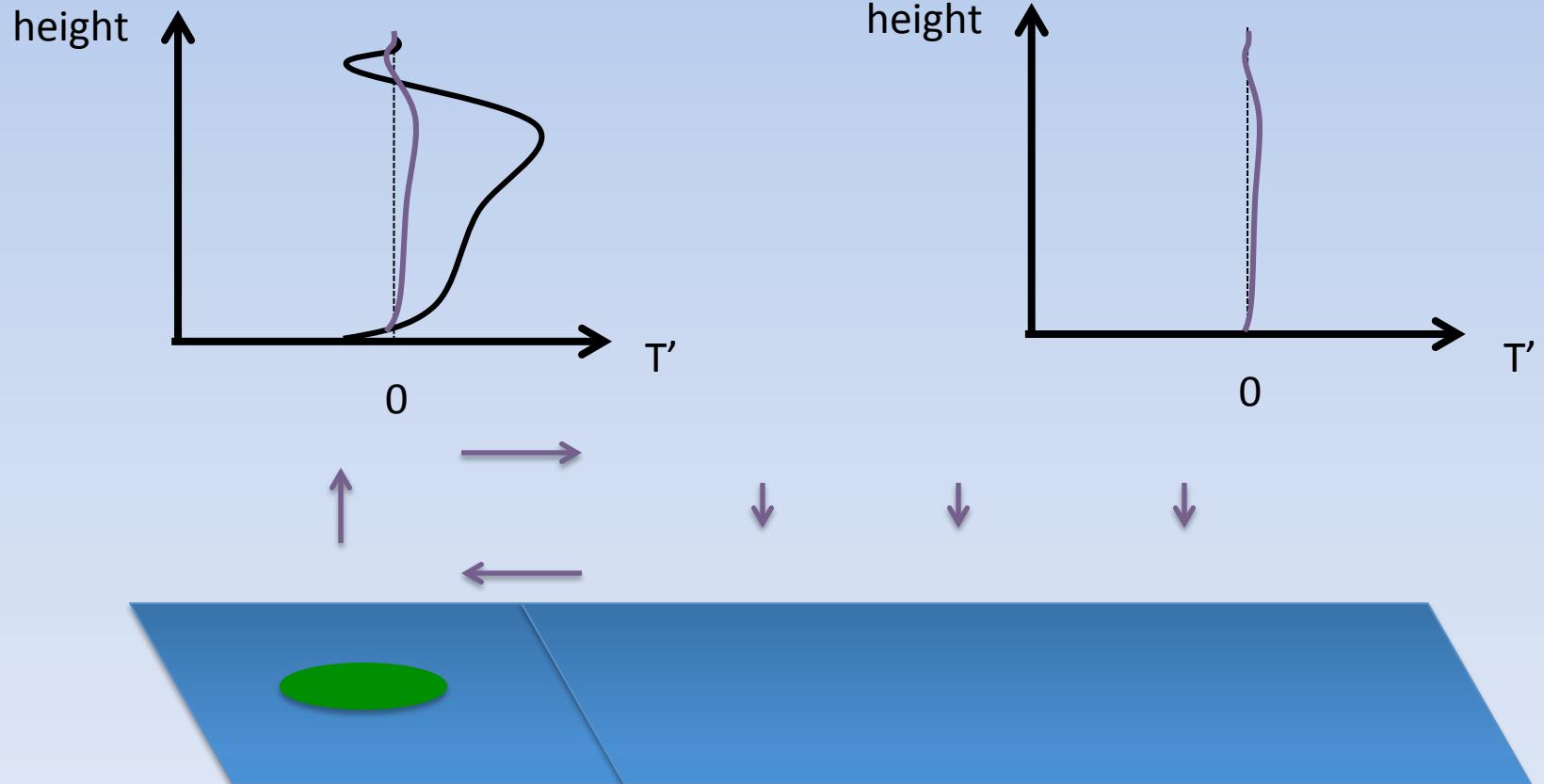


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All-ocean region

Domain-mean warming and circulation



Region with island(s)

All-ocean region

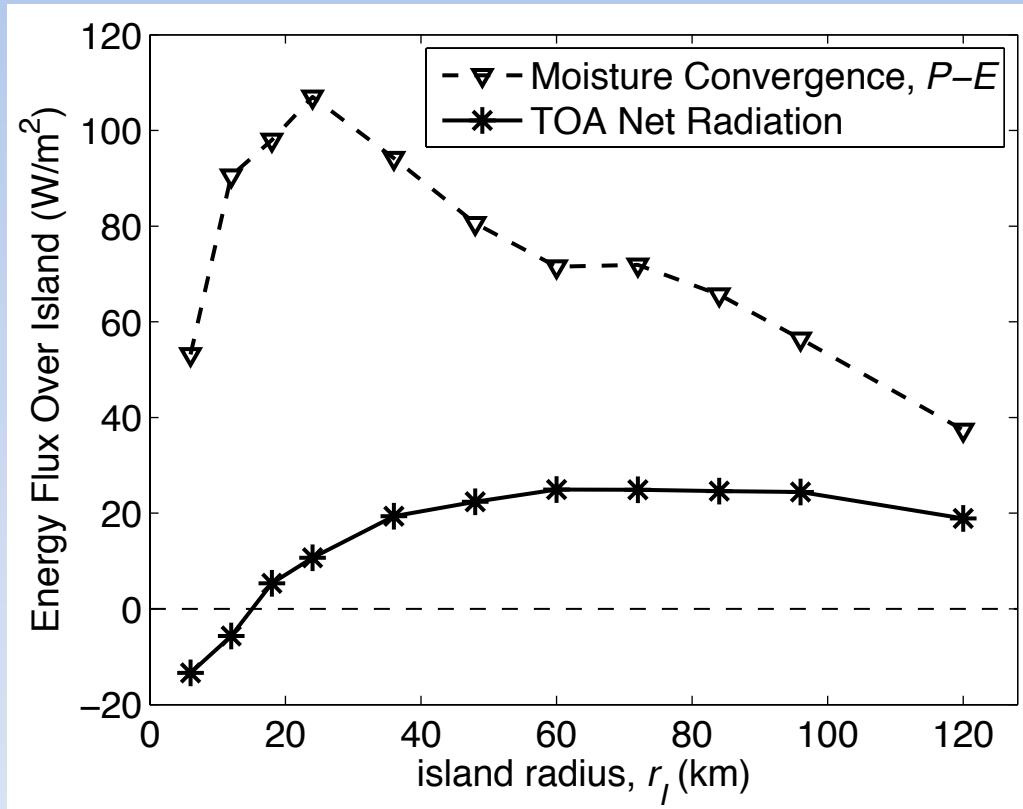
Results Summary

- Island rainfall enhancement and rectification of the diurnal cycle are simulated in an idealized framework, with a complex model
- Radiative rectification mechanism: cloud fraction covariance with the sun
- But convection-stability rectification mechanism may be more important
- Domain-mean warming and Walker circulation

Lessons/open questions from idealized modeling of island rainfall

- 1) Periodic forcing can rectify, especially where precipitation is concerned
- 2) It can be hard to apply time-mean thermodynamic constraints to circulations that oscillate in direction
- 3) In radiative-convective equilibrium, low surface heat capacity doesn't generally imply short memory

Moisture Convergence vs. Energy Balance



Gross moist stability perspective:

$$P-E = (F_{\text{TOA}} - F_{\text{surf}})/M = F_{\text{TOA}}/M \quad \text{over land}$$

GMS in reversing circulations

$$P-E = F_{\text{TOA}}/M$$

If I give the following pieces of information:

- 1) $M > 0$ at all times
- 2) $F_{\text{TOA}} > 0$ sometimes and < 0 at other times but
on average < 0

Q: Can we conclude that time-mean $P-E < 0$?

GMS in reversing circulations

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Q: Can we conclude that time-mean $P-E < 0$?

A: No. Take:

$$F_{\text{TOA}(\text{summer})} = 20 \text{ W/m}^2, M_{(\text{summer})} = 0.2 \rightarrow (P-E)_{\text{summer}} = 100 \text{ W/m}^2$$

$$F_{\text{TOA}(\text{winter})} = -40 \text{ W/m}^2, M_{(\text{winter})} = 0.5 \rightarrow (P-E)_{\text{winter}} = -80 \text{ W/m}^2$$

$$\text{Time-mean } P-E = 10 \text{ W/m}^2 > 0$$

$$(\text{Time-mean } F_{\text{TOA}} = -10 \text{ W/m}^2)$$

Lessons from idealized modeling of island rainfall

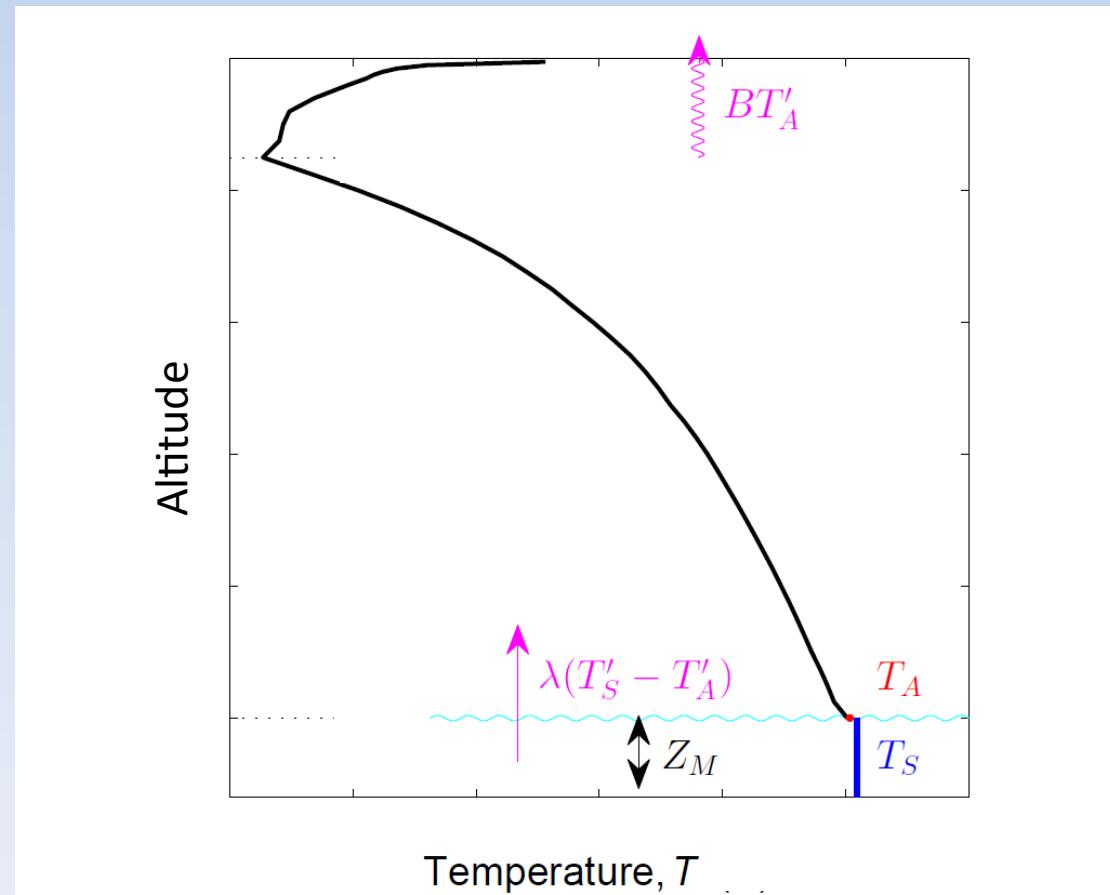
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Relaxation to Radiative-Convective Equilibrium

-What controls the relaxation time?

1. Heat Capacity or “thermal inertia,” C [units: J/K]
2. Heat transfer or exchange coefficient, B [units: W/K or J/K/s]

1. Heat Capacity:
 - A. Atmosphere
 - B. Ocean
2. Transfer Coefficient:
 - A. Top-of-atmosphere
 - B. Surface



Relaxation to Radiative-Convective Equilibrium

1. Heat Capacities:

C_A : Atmosphere*

C_S : Surface (Ocean or land)

2. Transfer Coefficients:

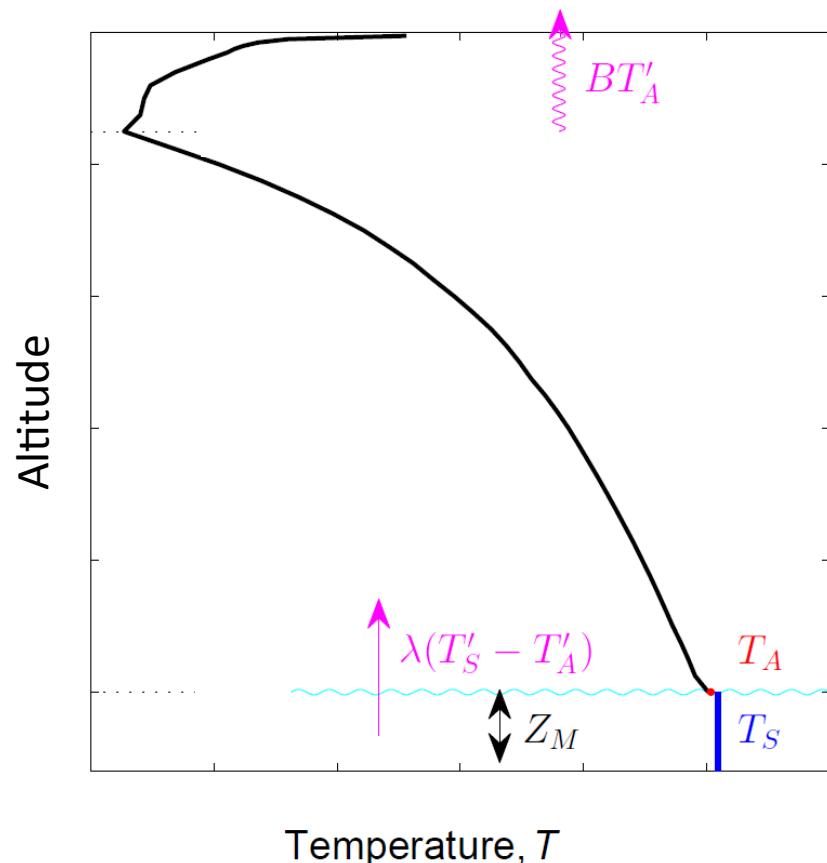
B : Top-of-atmosphere

λ : Surface

$$\tau_A = C_A / (\lambda + B)$$

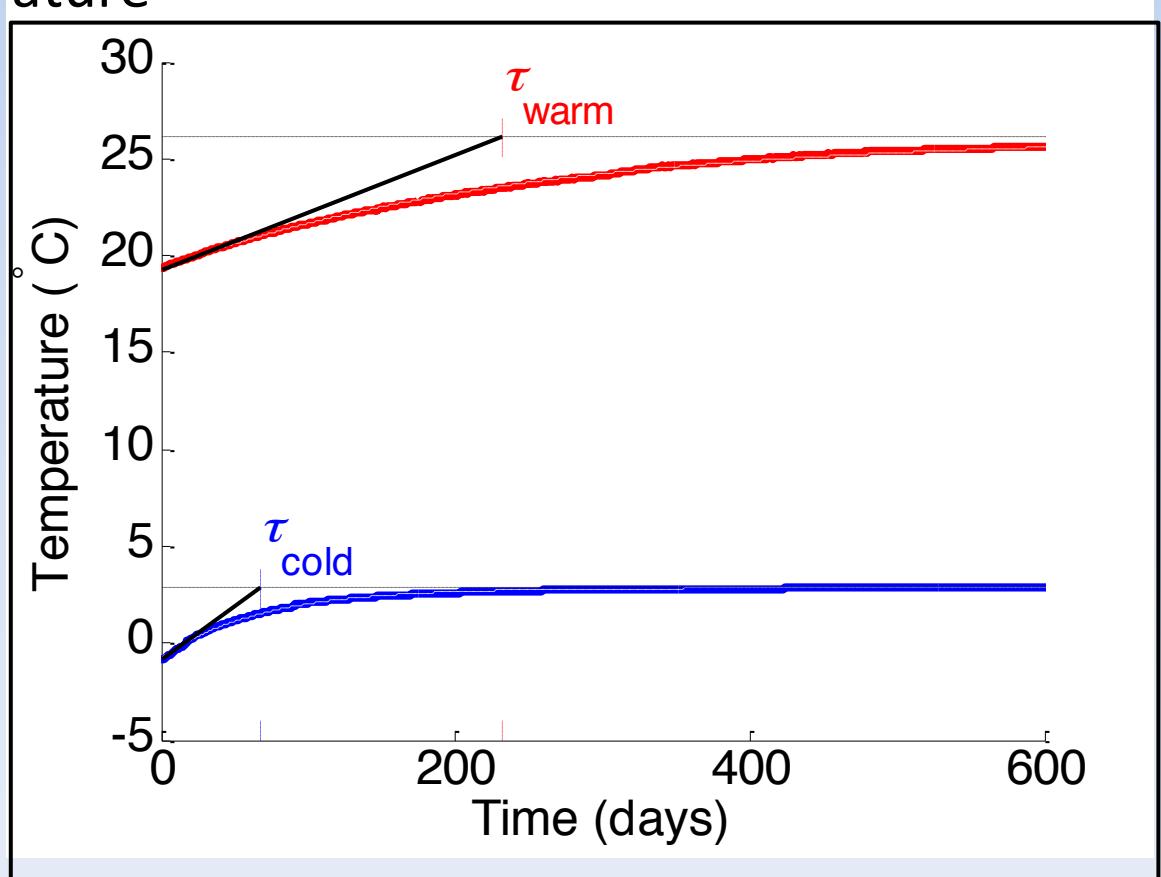
$$\tau_S = C_S / \lambda$$

$$\tau_C \approx \frac{\lambda + B}{B} (\tau_A + \tau_S)$$



Relaxation time scale in RCE

- Simulations of radiative-convective equilibrium with a single-column model, with a 0.5-meter slab of water as the surface
- Atmospheric heat capacity at constant relative humidity increases systematically with temperature



Thanks!

See also:

- Cronin, Emanuel, and Molnar, 2015, QJRMS, “Island precipitation enhancement and the diurnal cycle in radiative-convective equilibrium”
- Molnar and Cronin, 2015, Paleoceanography, “Growth of the Maritime Continent and its possible contribution to recurring Ice Ages”
- Cronin and Emanuel, 2013, JAMES, “The climate time scale in the approach to radiative-convective equilibrium”

Timing of rainfall over land and sea

- GCMs poorly simulate the timing of peak rainfall over land

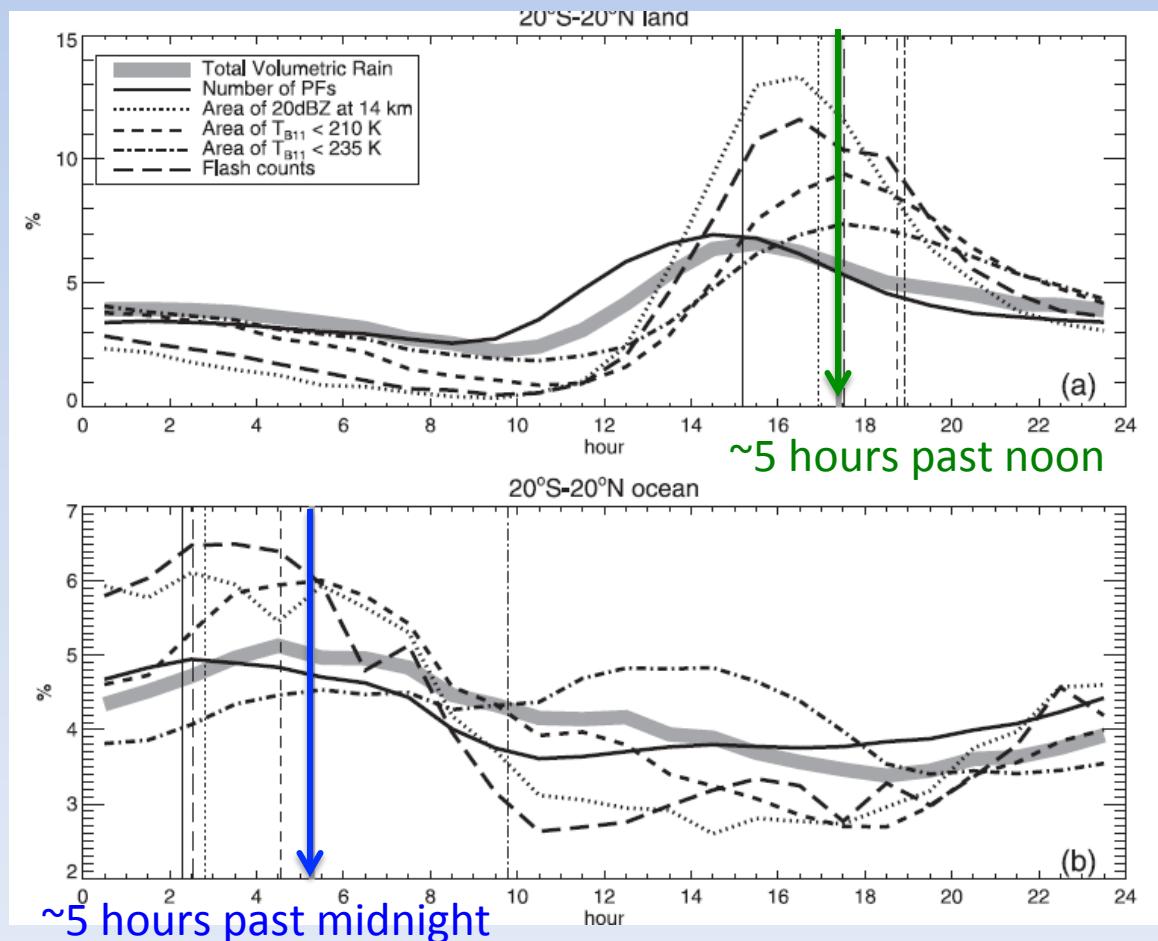
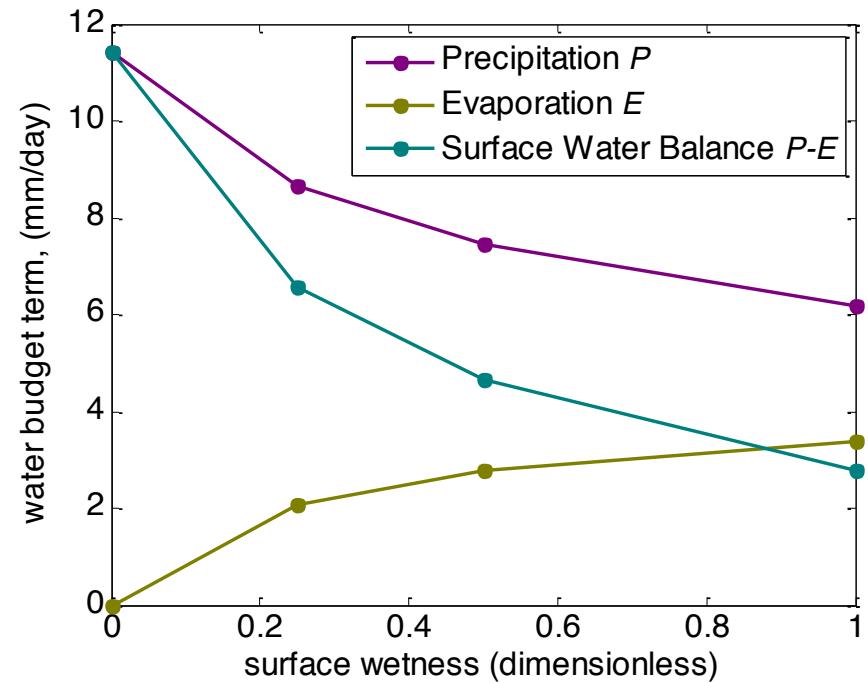
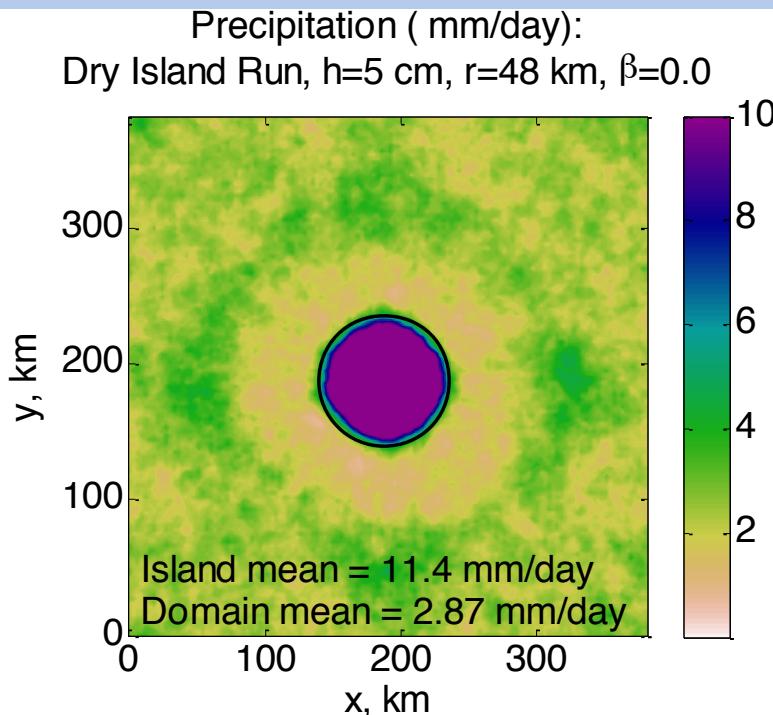


Figure from: *Liu and Zipser (2008), GRL*

Surface wetness and island rainfall



- “Parking Lot” island with no surface evaporation: rains more!
- Negative ‘soil moisture’-precipitation feedback