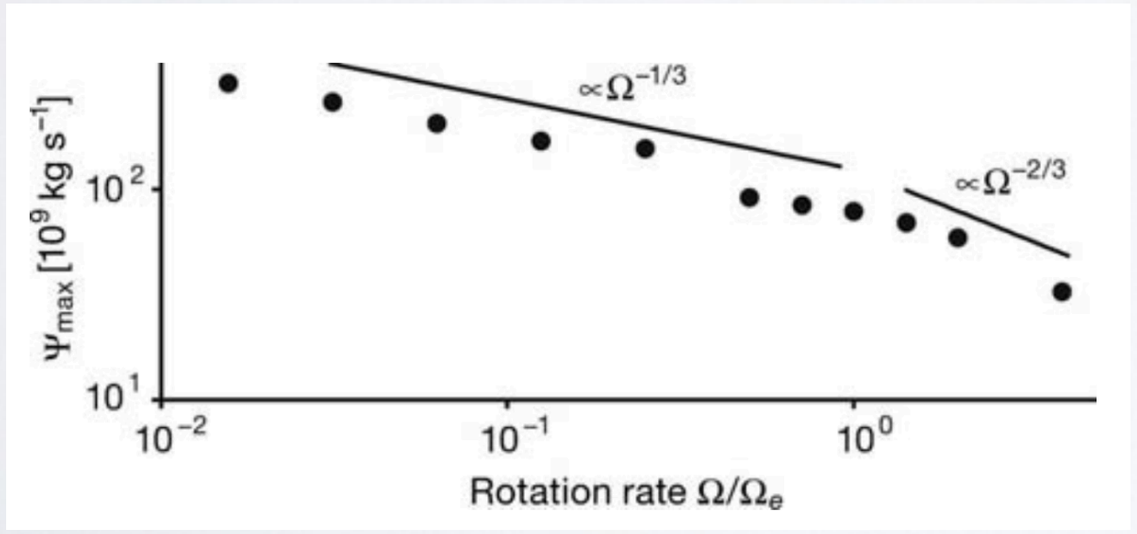
The ω-governor

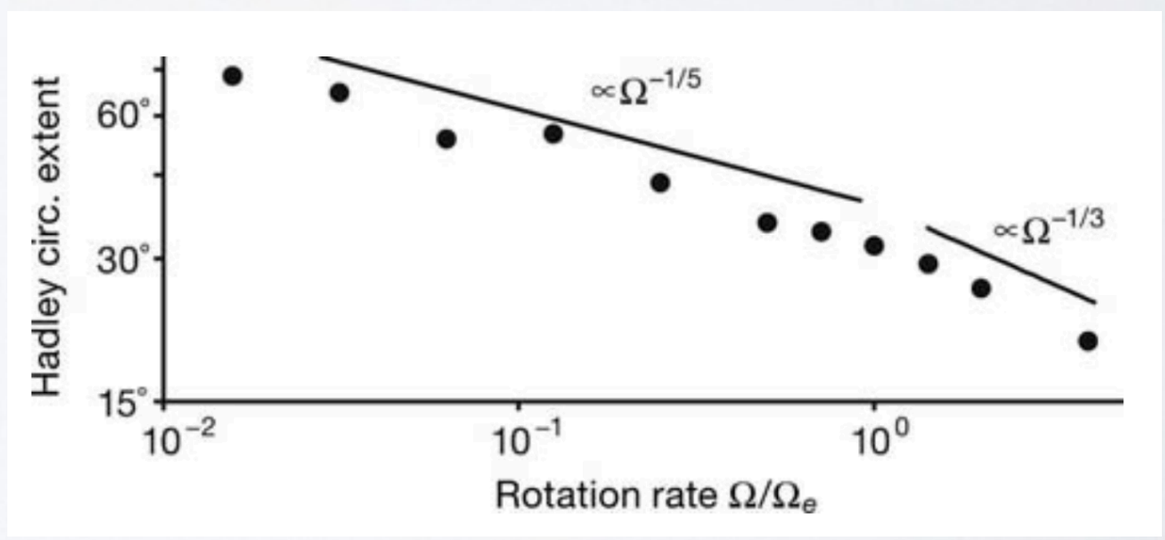
Jonathan L. Mitchell[1]
Spencer Hill[1,2]

[1]UCLA [2]Caltech

The Motivation

- Hadley cell expansion in global warming (e.g., Lu et al. '07, Vallis et al. '15)
- Scalings of Hadley cell width and strength with rotation rate don't obey axisymmetric theory
- Held & Hou '80: $\varphi_{max} \sim \Omega^{-1}$ $\Psi_{max} \sim \Omega^{-3}$





Walker & Schneider '06

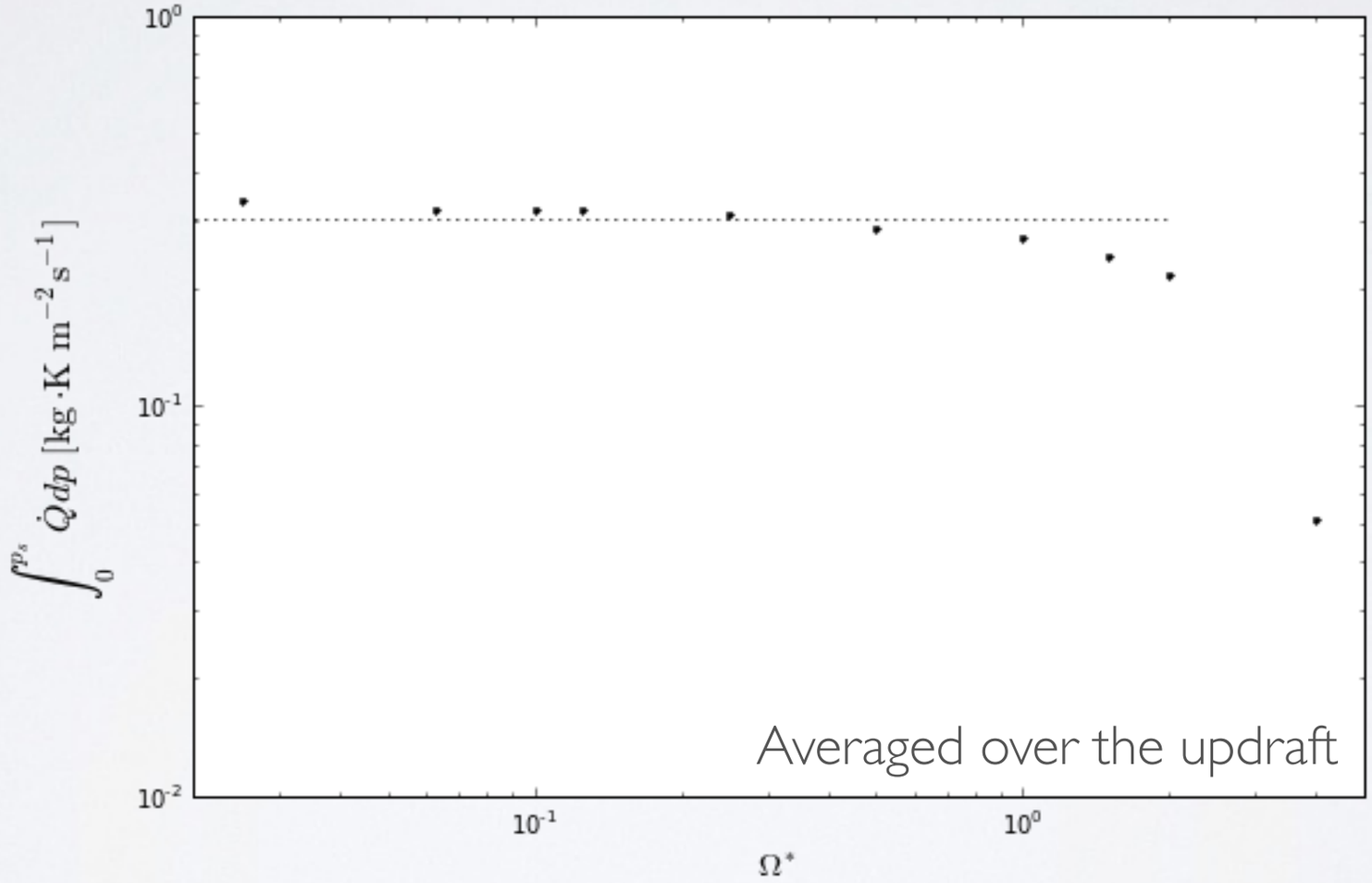
The (Dry Dynamics) Problem

- Models tend toward eddy-driven Hadley cell strengths, i.e., small Ro on poleward flank (Walker & Schneider '06)

- WTG conditions in the tropics implies a balance between radiative and advective heating (provided convection is isolated to the ITCZ; Sobel et al. '01, but see caveats in Singh & Kuang '16)

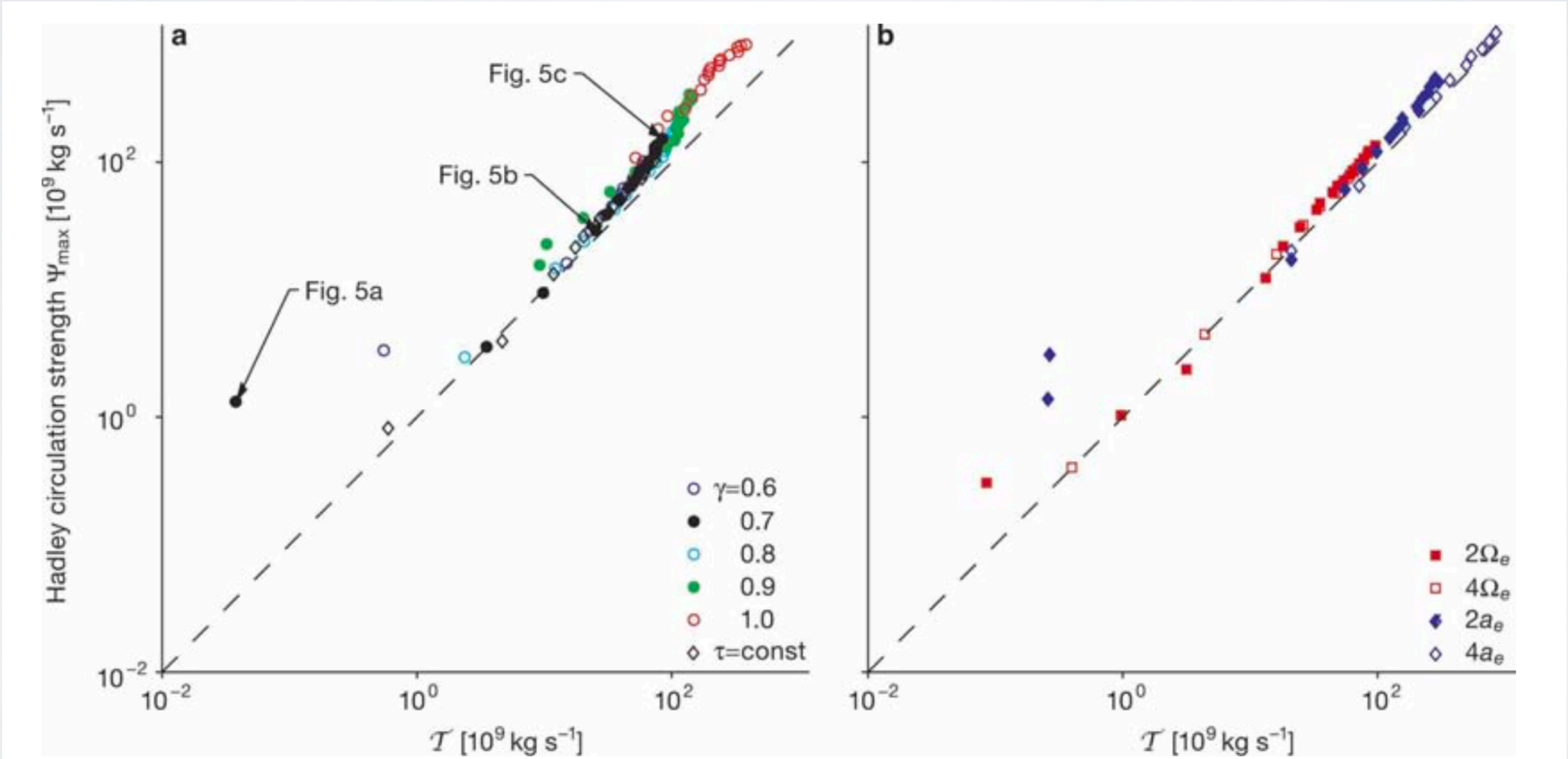
- Radiative cooling is not strongly sensitive to planetary parameters

Column-Integrated Radiative Fluxes Don't Depend On Rotation Rate



Assumption #1: Ro ≪ 1
Eddy-Regulated Hadley Cell Strength

- Walker & Schneider '06



Assumption #2: The ω-governor
Vertical Velocities Governed By Radiative Cooling

- This is not at all new…
  - Schneider & Lindzen '76, Held & Hou '80, Singh & Kuang '16, many others
  - Used in tropical studies with weak temperature gradients (Sobel et al '01)

$$\bar{\omega}\frac{\partial\bar{\theta}}{\partial p} = \overline{Q_R}$$

- If static stability and radiative cooling are fixed

$$\bar{\omega} \sim \text{constant}$$

Combine Assumptions: Hadley Cell Width Adjusts To Accommodate Eddy-Driven Mass Flux

- #1: Eddy momentum flux convergence requires a certain mass flux to balance momentum (small Ro)

$$f\bar{v} \sim -s \rightarrow \Psi_{\max} \sim \frac{S}{f}$$

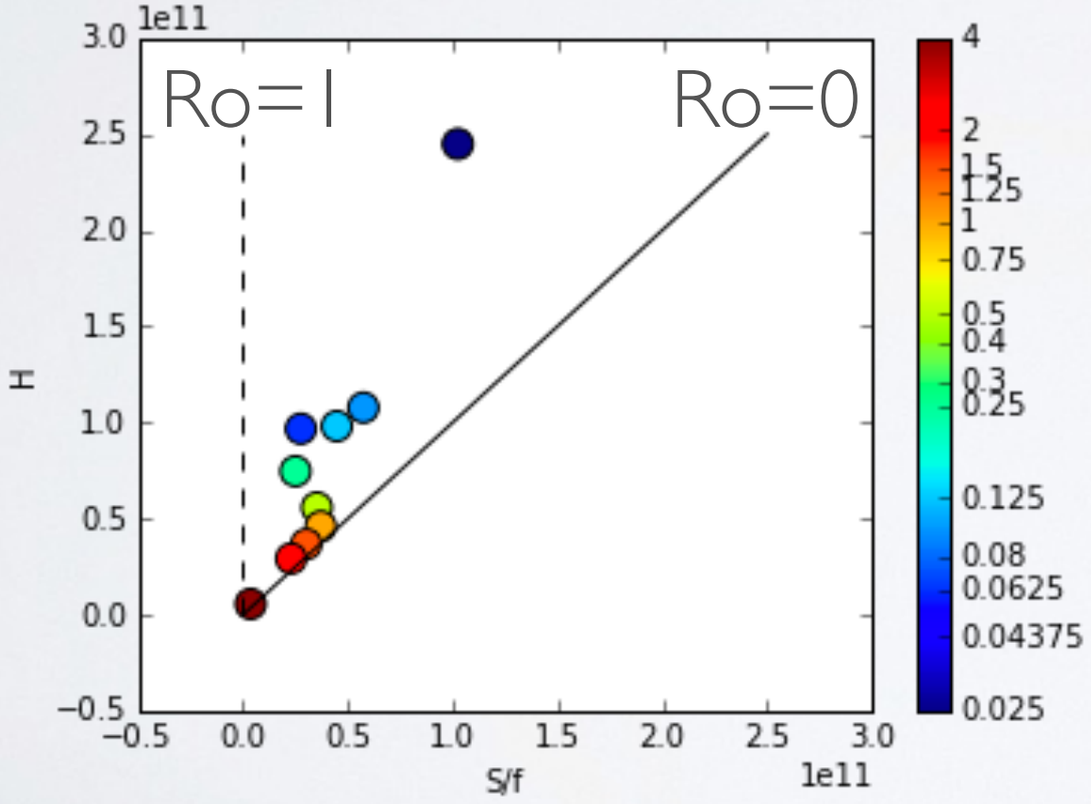
- #2: Average updraft velocity is externally fixed (**ω**-governor)
  - ***Key concept***: With fixed vertical velocity, the Hadley cell must widen to flux more mass…

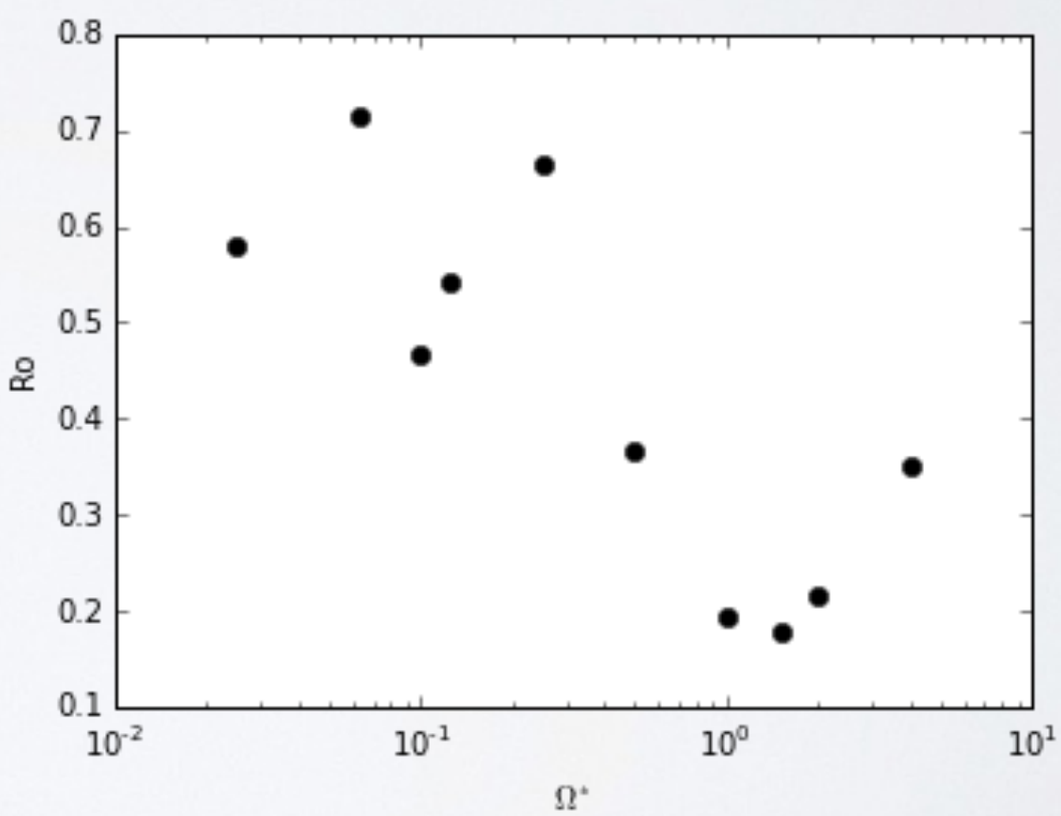
$$\Psi \sim \frac{\omega}{g} a \Delta y \propto y_h$$

- *Result: Width & strength scale as the eddy fluxes, S/f*

Testing Assumption #1: Singh-Kuang Plot

- Held-Suarez simulations for $\Omega^* \sim \{10^{-2}:10^{1}\}$ have Ro ≲ 0.5

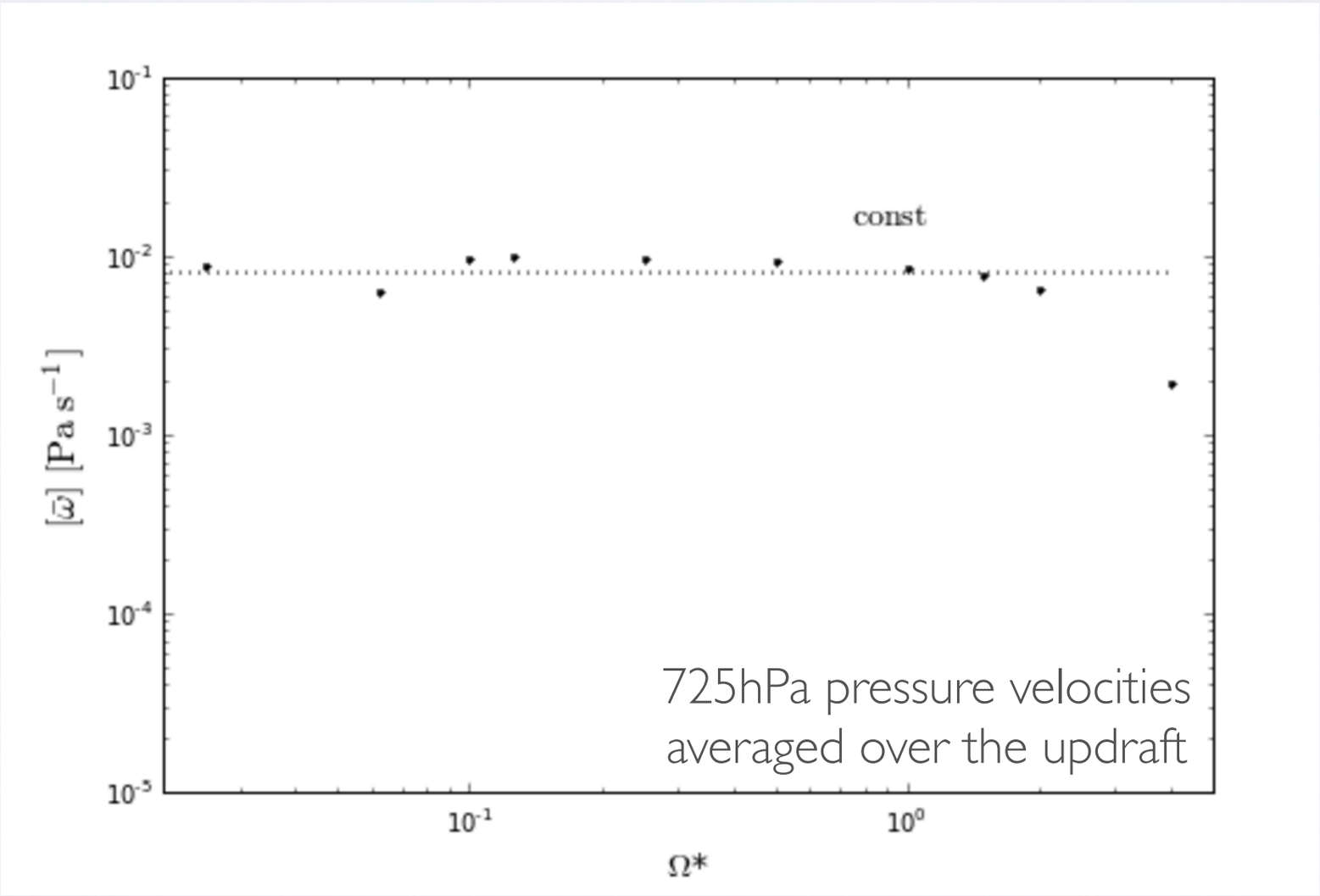




$$H(1 - Ro) \sim \frac{S}{f}$$

Testing Assumption #2: Vertical Velocities

- Held-Suarez simulations for Ω^* ~ {10^{-2}:10^{1}} have ω~constant



Combine Assumptions: Hadley Cell Width Adjusts To Accommodate Eddy-Driven Mass Flux

- #1: Eddy momentum flux convergence requires a certain mass flux to balance momentum (small Ro)

$$f\bar{v} \sim -s \rightarrow \Psi_{\max} \sim \frac{S}{f}$$

- #2: Average updraft velocity is externally fixed (**ω**-governor)
  - ***Key concept***: With fixed vertical velocity, the Hadley cell must widen to flux more mass…

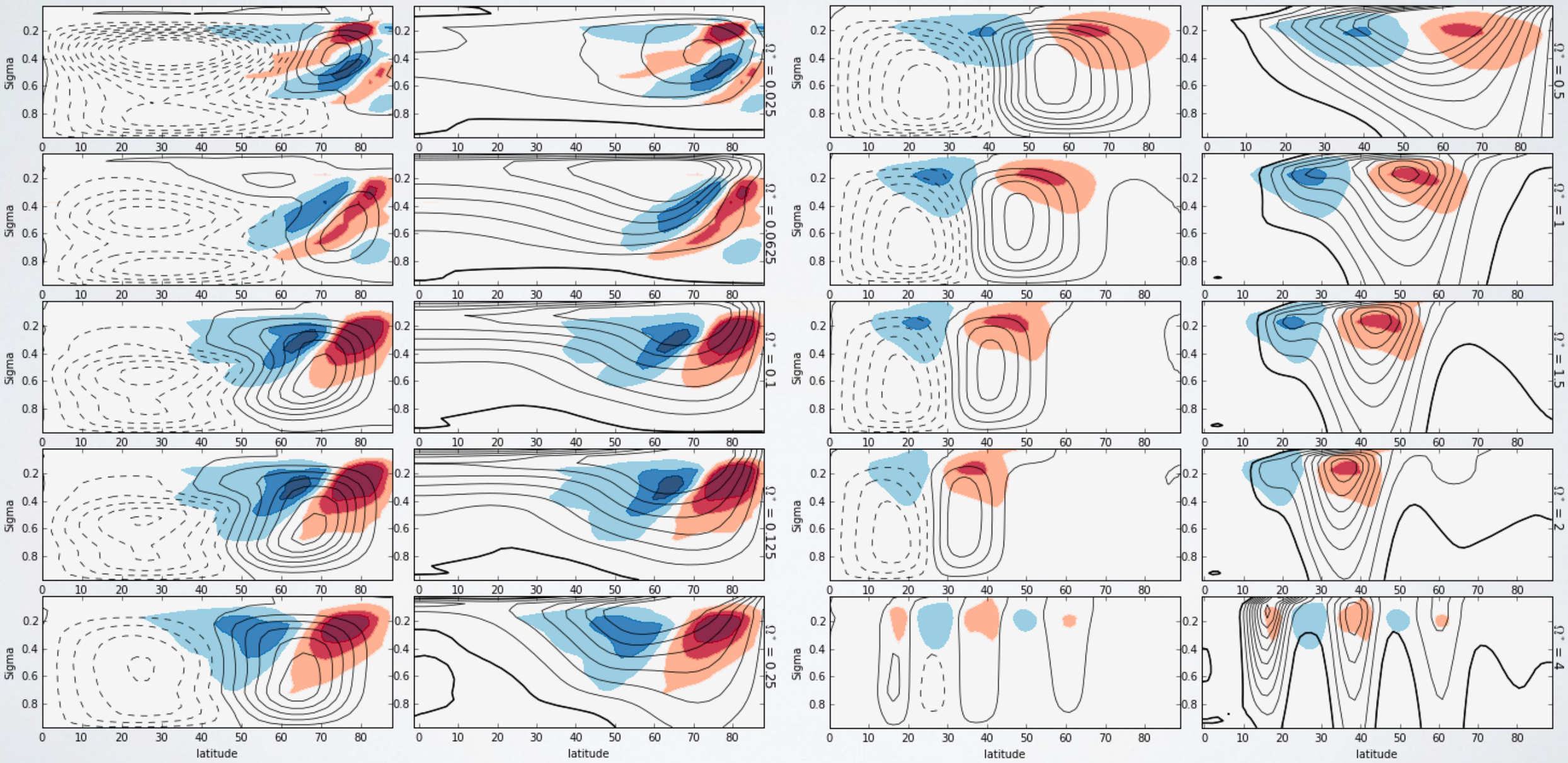
$$\Psi \sim \frac{\omega}{g} a \Delta y \propto \phi_h$$

- *Result: Width & strength scale as the eddy fluxes, S/f* ??

Eddy Momentum Flux Convergence, Mass Flux, And Winds

Hadley cell gets weaker and wider with rotation rate

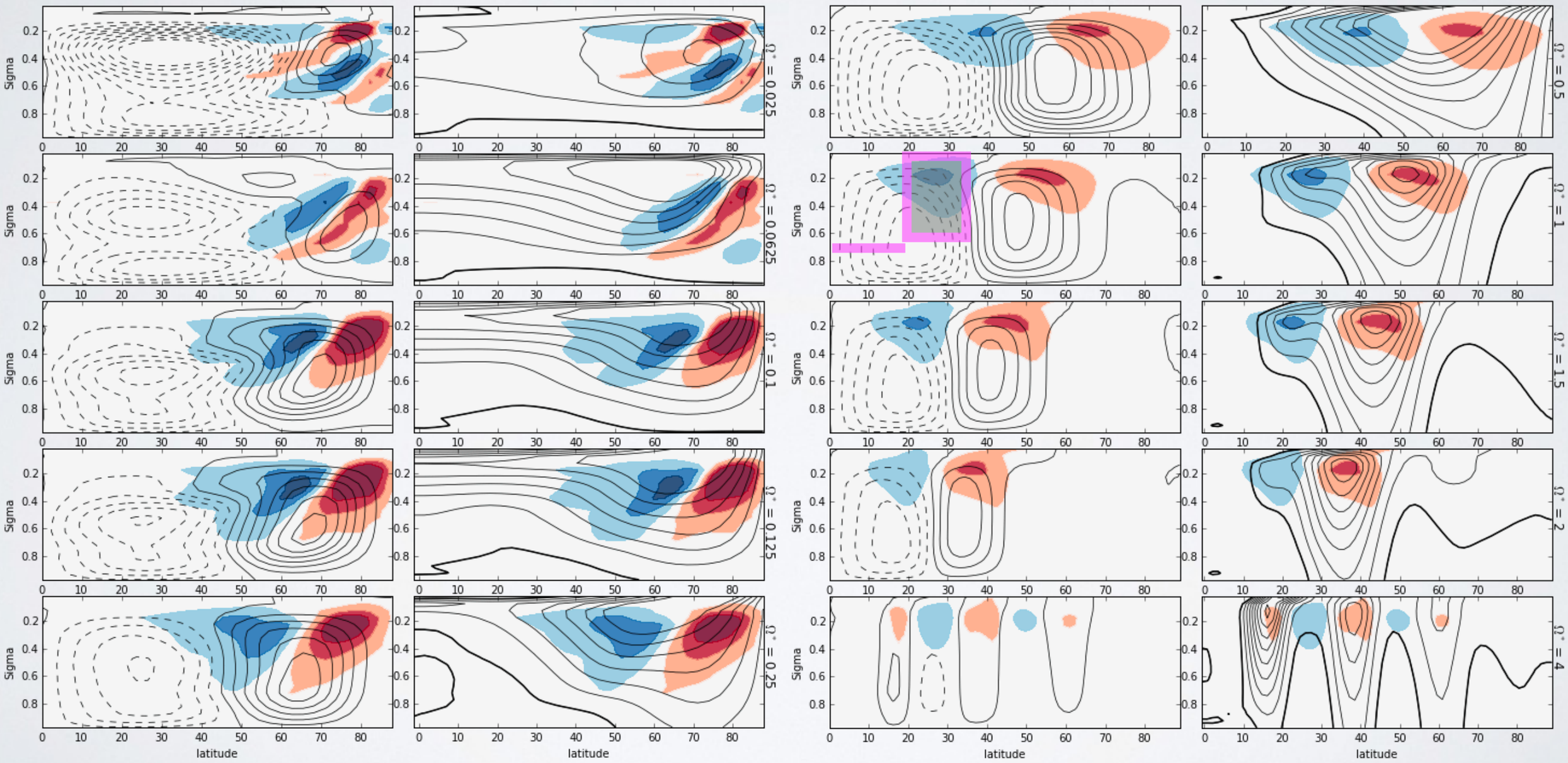
slow rotation



fast rotation

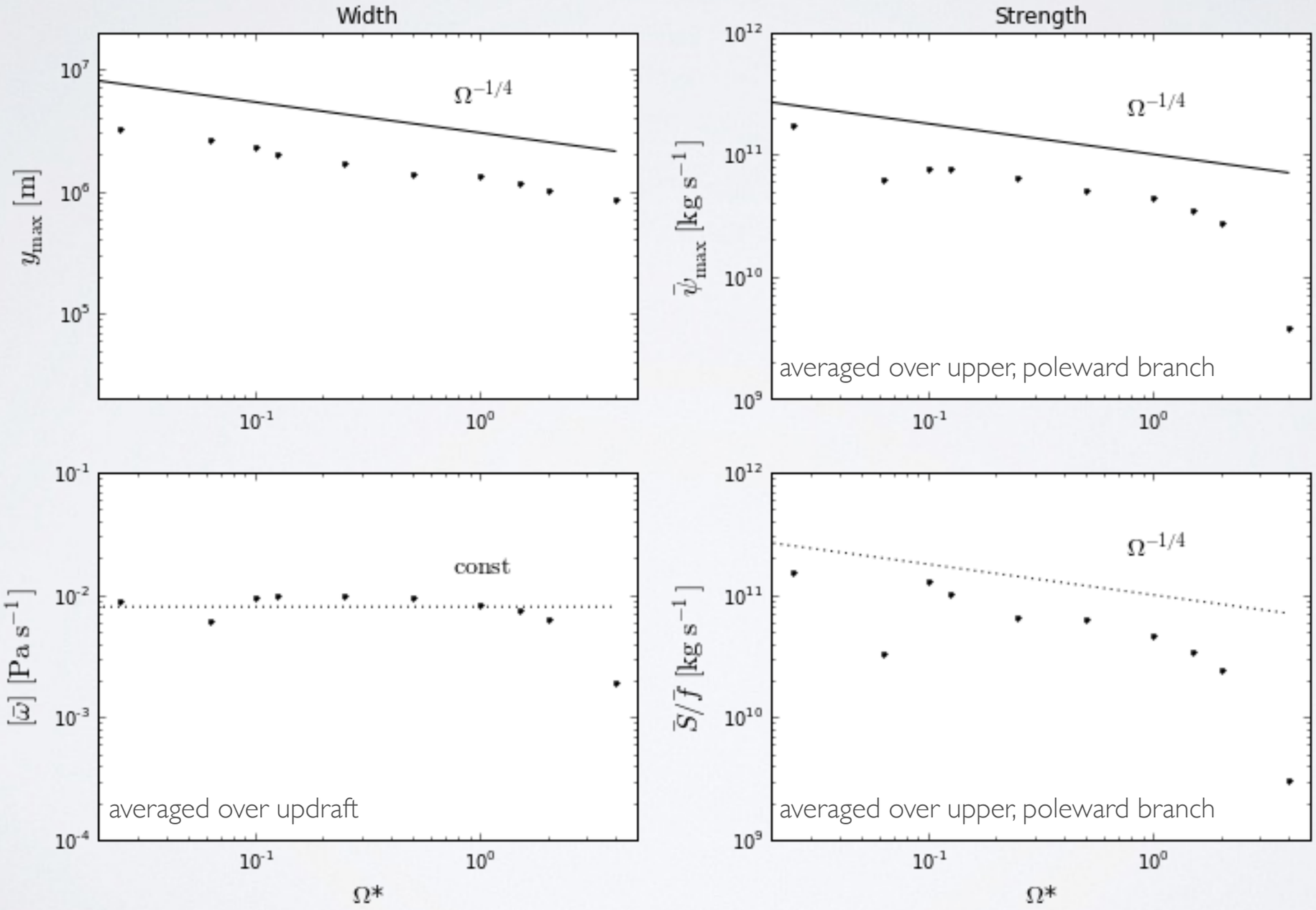
Eddy Momentum Flux Convergence, Mass Flux, And Winds

slow rotation



fast rotation

Width And Strength Have The Same Scaling, Set By Eddy Momentum Flux Convergence

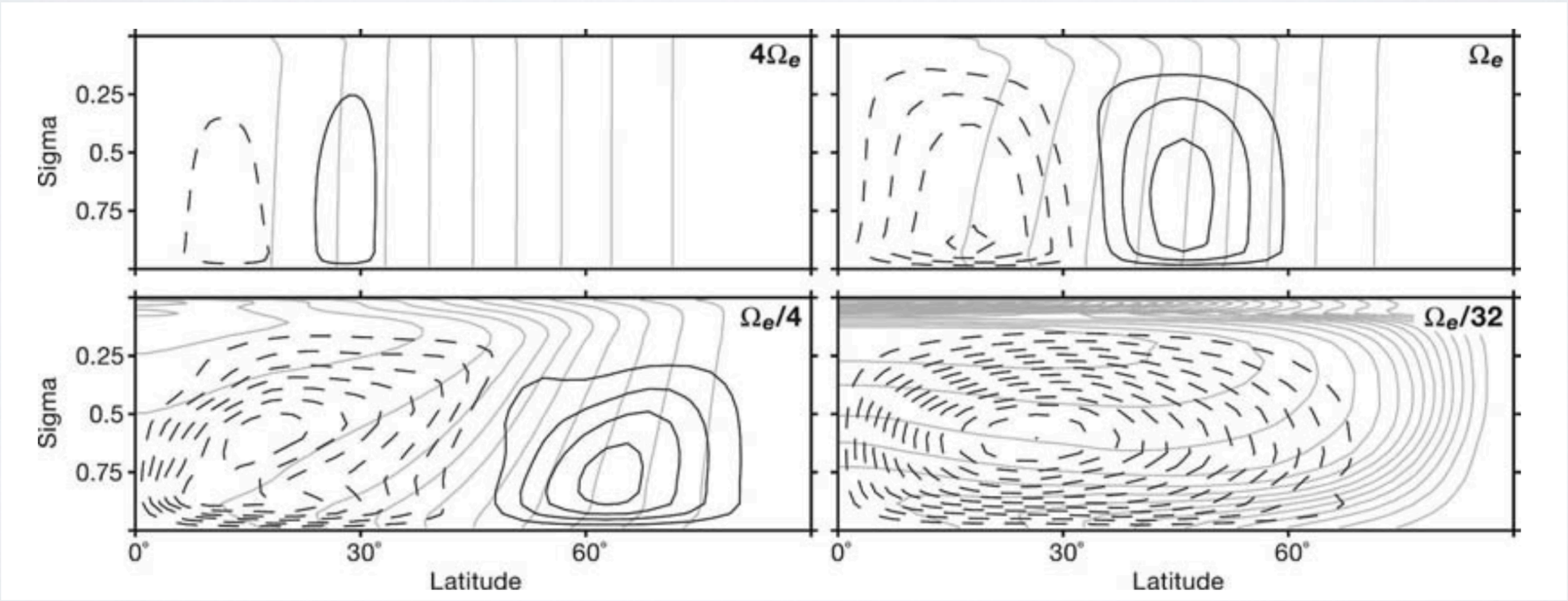


Note: S/f is an input (not a closed theory)

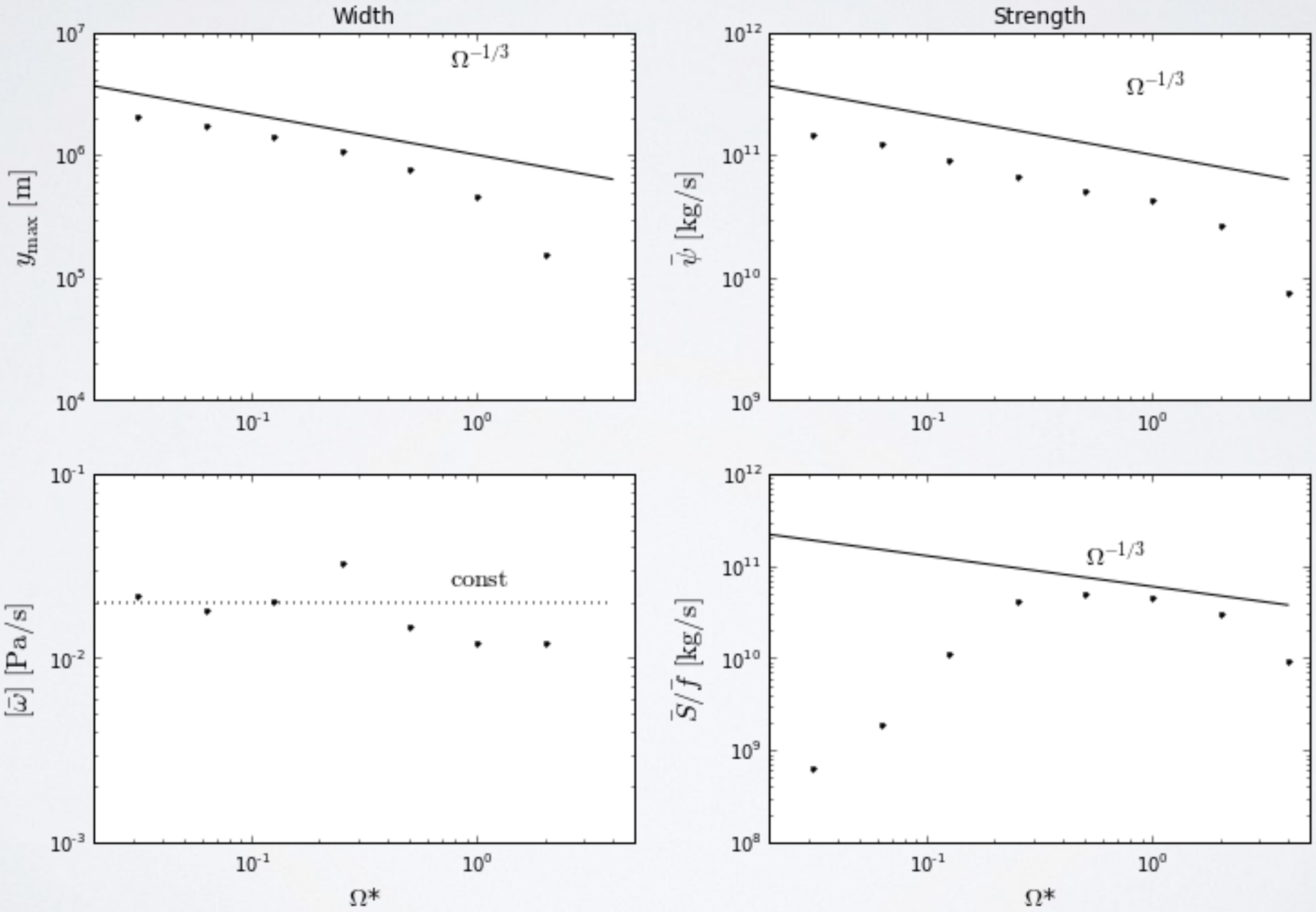
What About A Different Forcing Scheme?

- "Caltech model": Schneider '04
  - ITCZ-like forcing in the deep tropics, with convective adjustment
  - Uniform Newtonian cooling elsewhere; idealized boundary layer

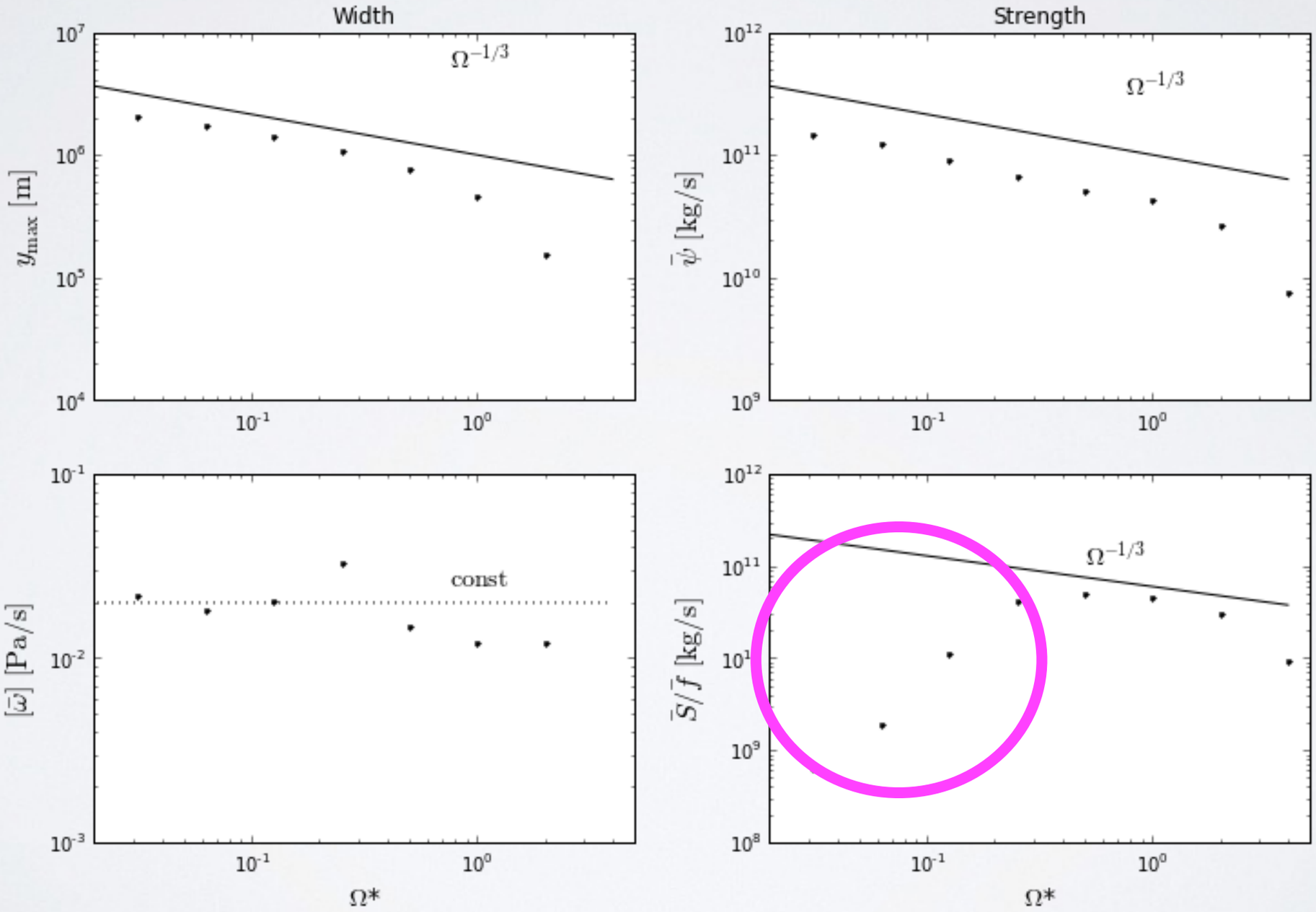
Walker & Schneider '06



Width And Strength Have Same Scaling, But Neither Closely Follow The Eddy Fluxes

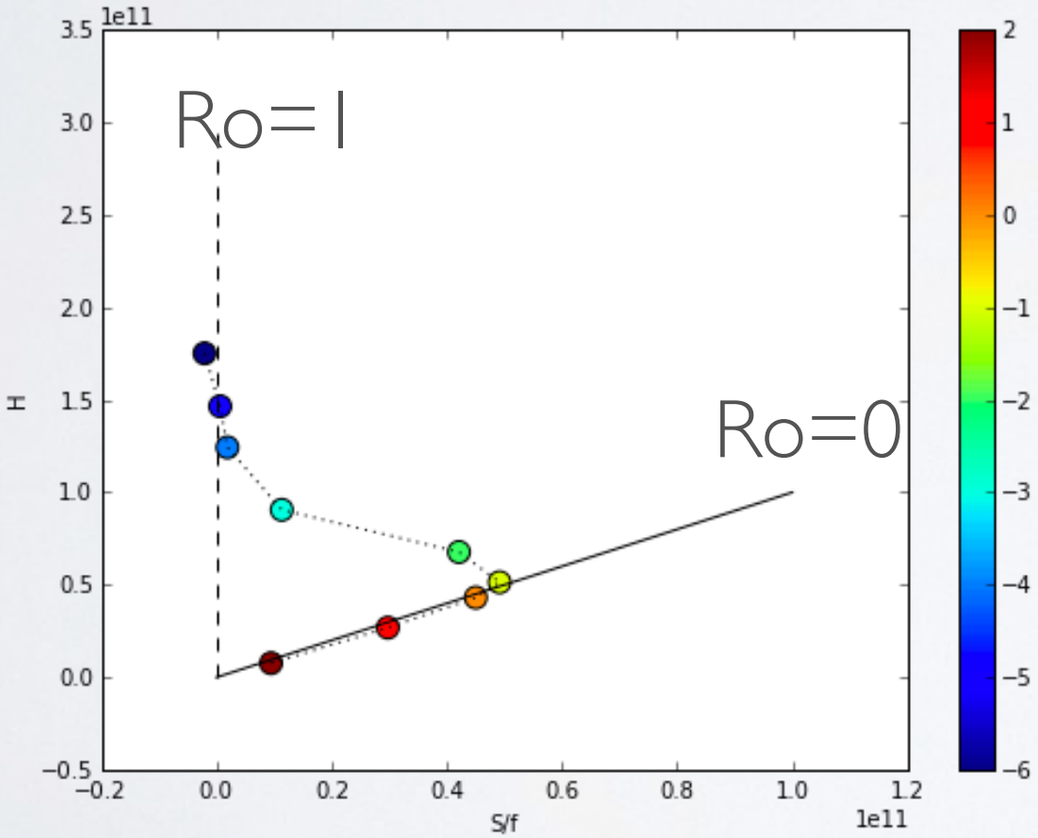


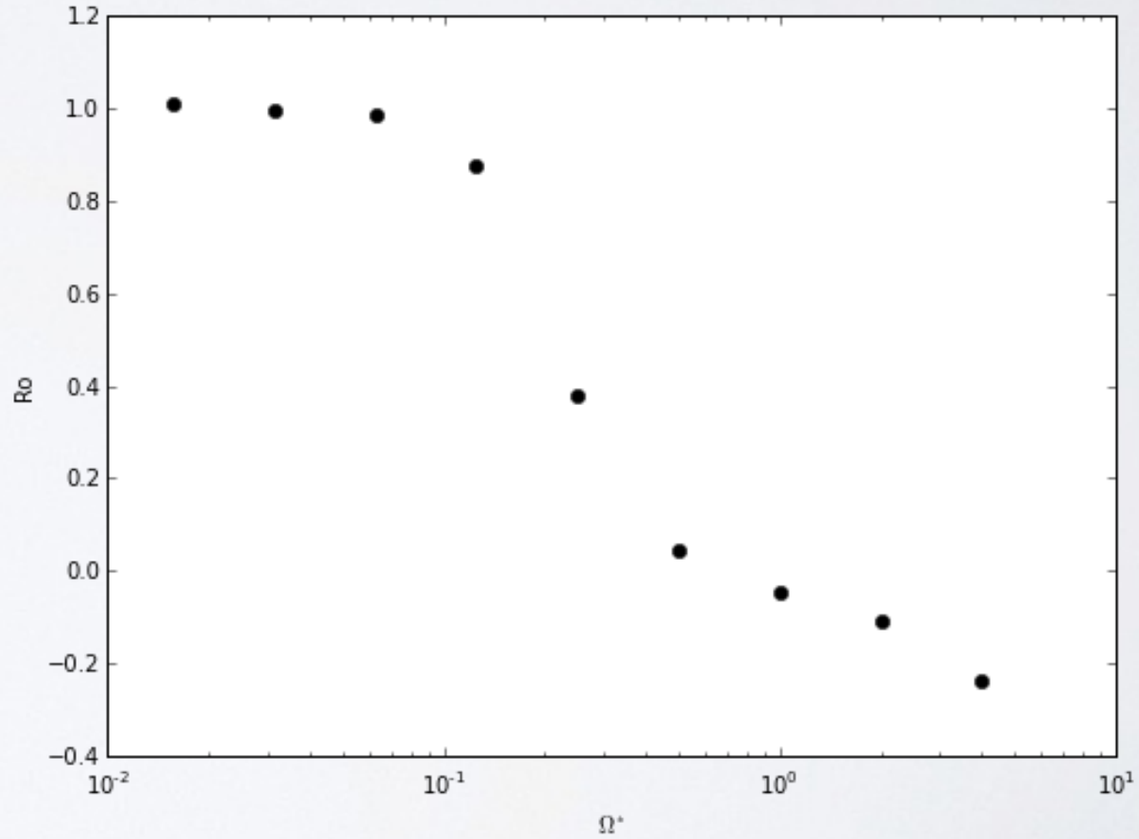
Width And Strength Have Same Scaling, But Neither Closely Follow The Eddy Fluxes



Caltech Model Results: Singh-Kuang Plot

- Ro is not always small, varies to compensate changing S/f:

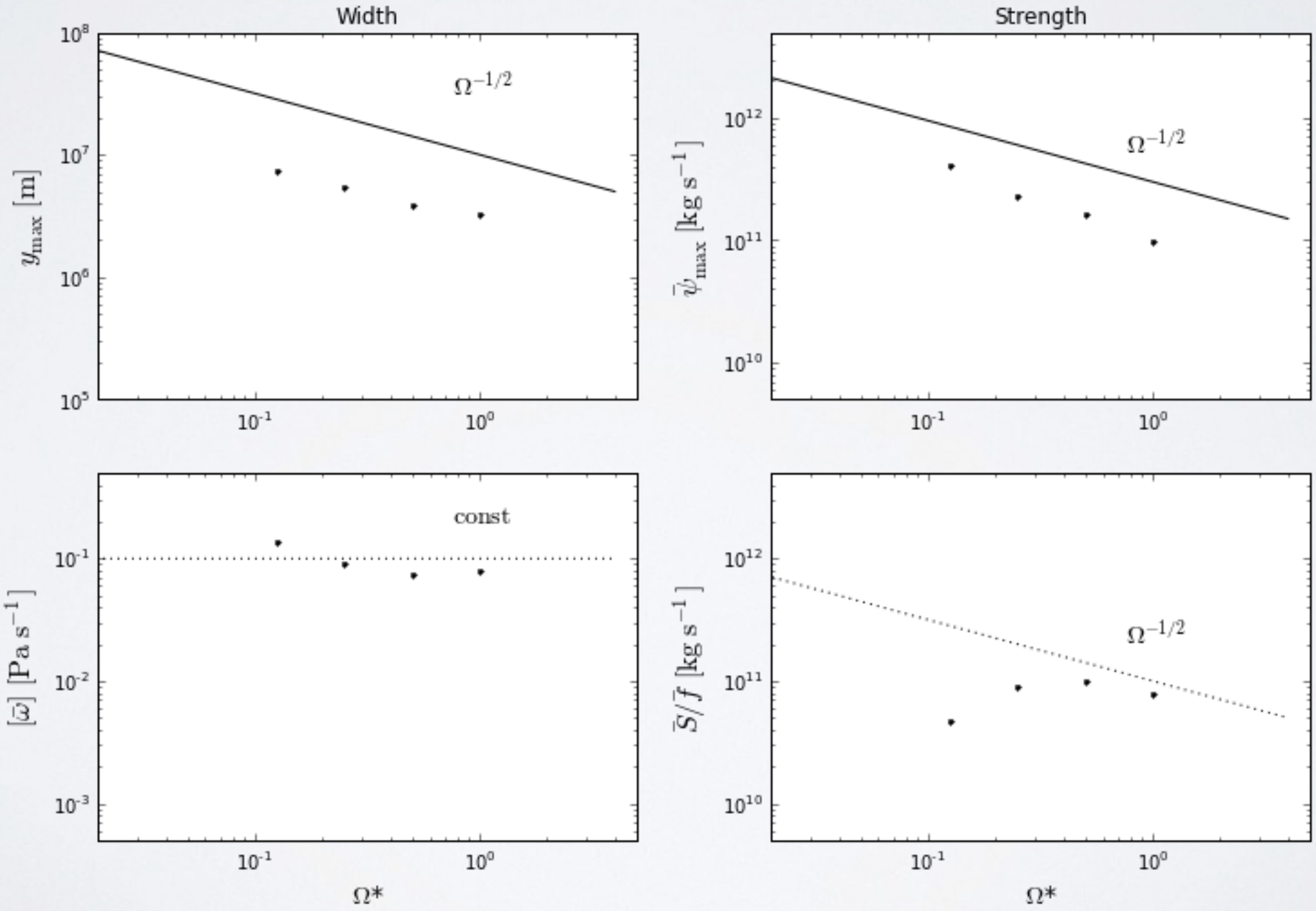




$$H(1 - Ro) \sim \frac{S}{f}$$

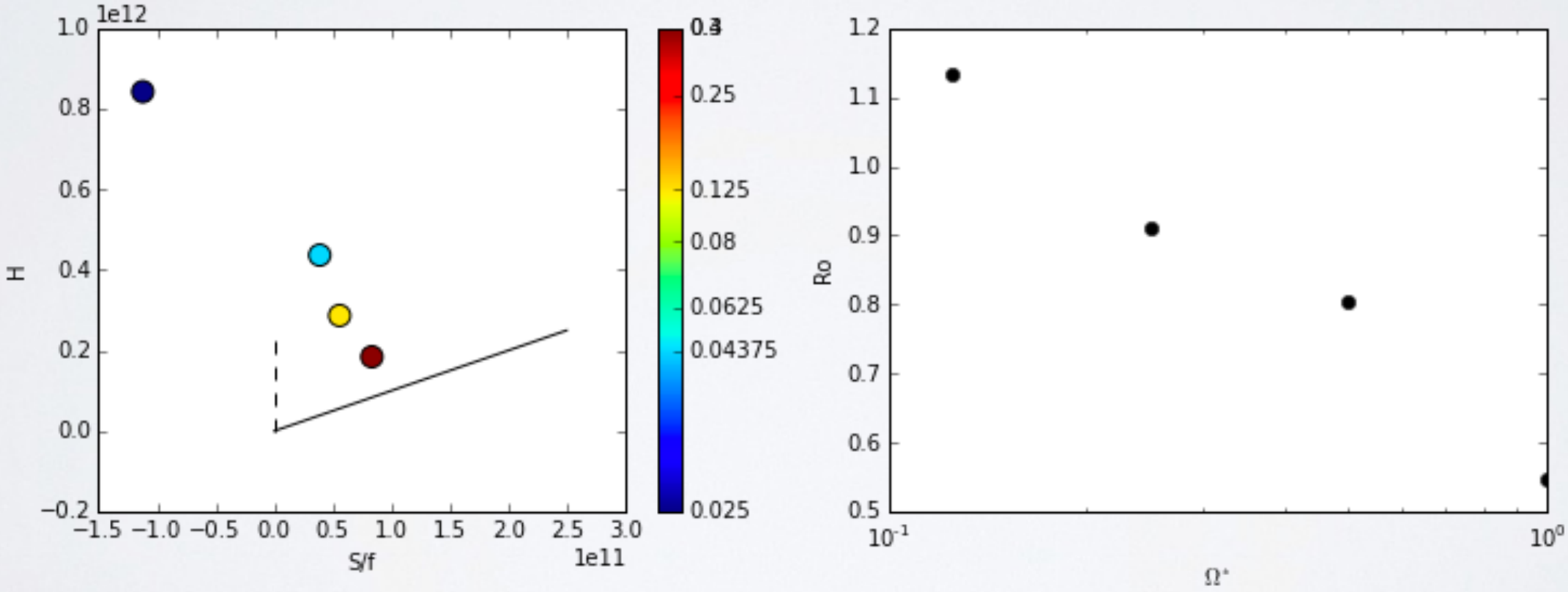
Slab Aquaplanet Model
(Frierson, O'Gorman Schneider)

- Width & strength scale together, but again don't follow eddies



Slab Aquaplanet Model
(Frierson, O'Gorman Schneider)

- Ro-number compensation again evident…

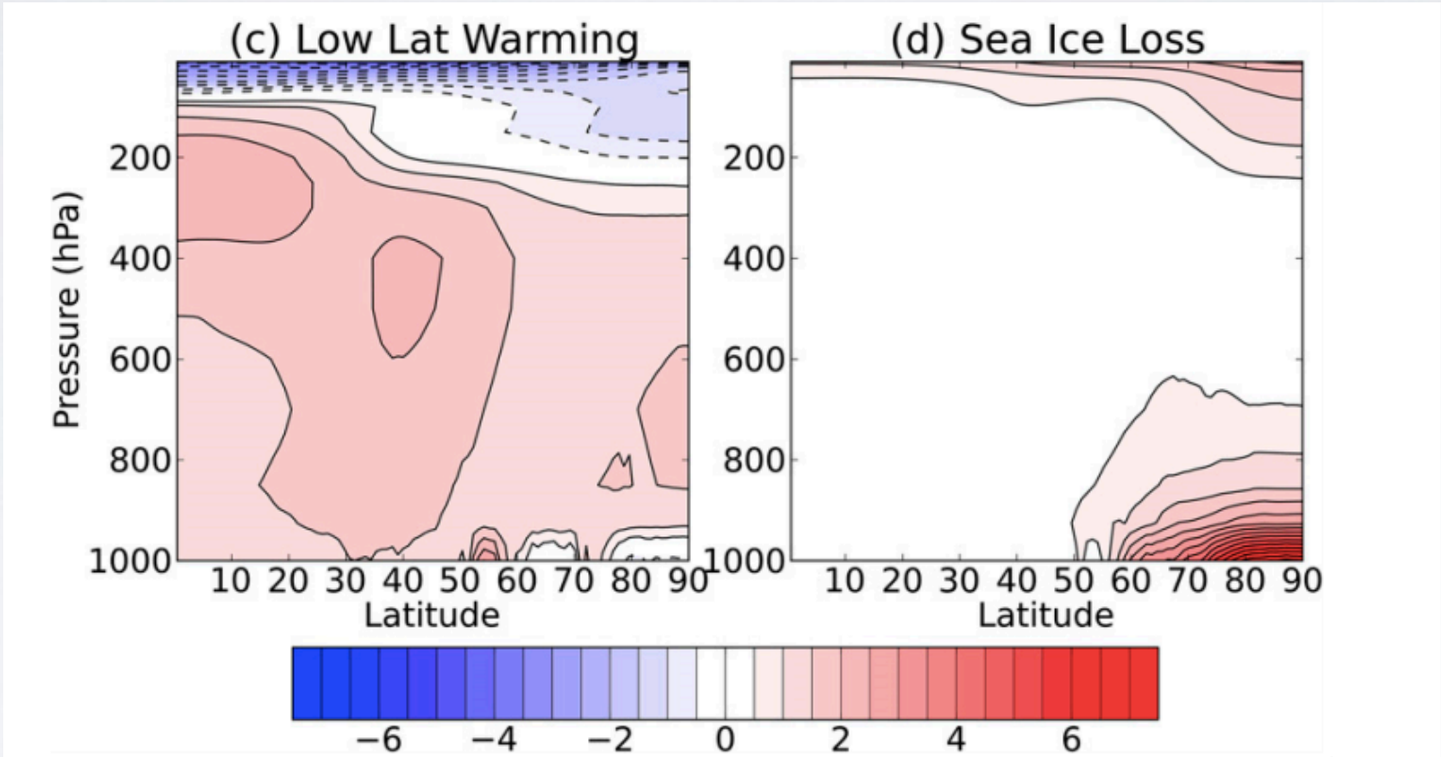


The Earth's Hadley Cell Is In An Eddy-Dominated Regime

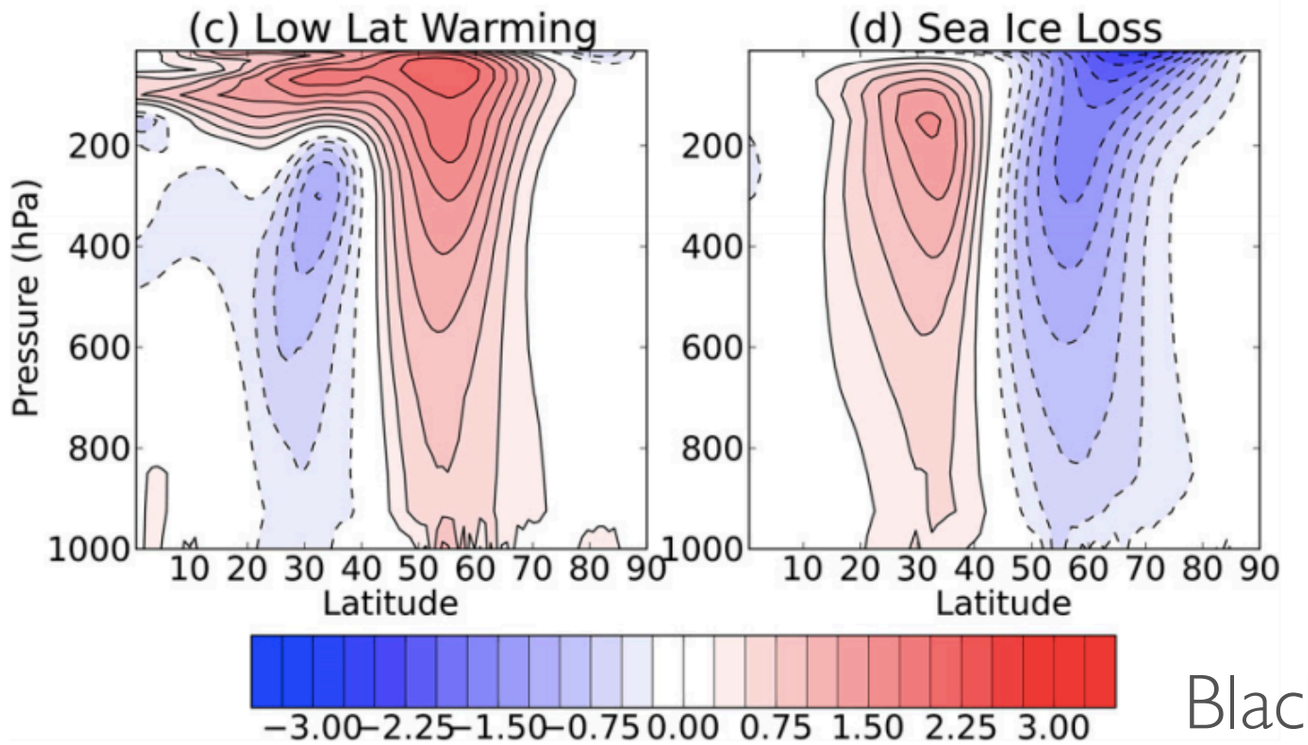
What does this imply for global warming…?

Sea Ice Reduction Causes Weaker Eddies Which May Counteract Hadley Cell Expansion

dT



dU



Blackport & Kushner 17

Summary

- Mean vertical velocity of the Hadley cell updraft shows little sensitivity to rotation rate, regardless of model forcing.
  - Radiative-advective thermal balance approximately holds.
  - Radiative cooling is insensitive to rotation rate.
  - "The ω-governor"

- In the small-Ro regime, eddy momentum flux convergences drive the mass flux of the Hadley cell.

- Taken together, the Hadley cell can only increase mass flux by increasing its width.

- Result: Width and strength have the same scaling, which is determined by the eddy momentum flux convergence.

- Sea-ice decline weakens eddies, which may counteract Hadley cell expansion