

Thermodynamic and dynamic controls on the Hadley circulation

Martin Singh & Zhiming Kuang
Harvard University

Monsoons: Past, Present and Future
California Institute of Technology
May 2015

What controls the strength of the Hadley circulation?

- Large-scale eddies influence the Hadley cell through momentum fluxes
 - (e.g., Walker & Schneider, 2006; Bordoni & Schneider, 2008; Caballero, 2007)
- Convection may also be important for momentum budget (& thermodynamic budget)
 - (Voigt et al., 2012; Zhang & McFarlane, 1995; Wu et. al, 2003; Richter & Rasch, 2008)
- Is the momentum budget the best lens through which to understand the Hadley circulation?
 - i.e., what about thermodynamics?

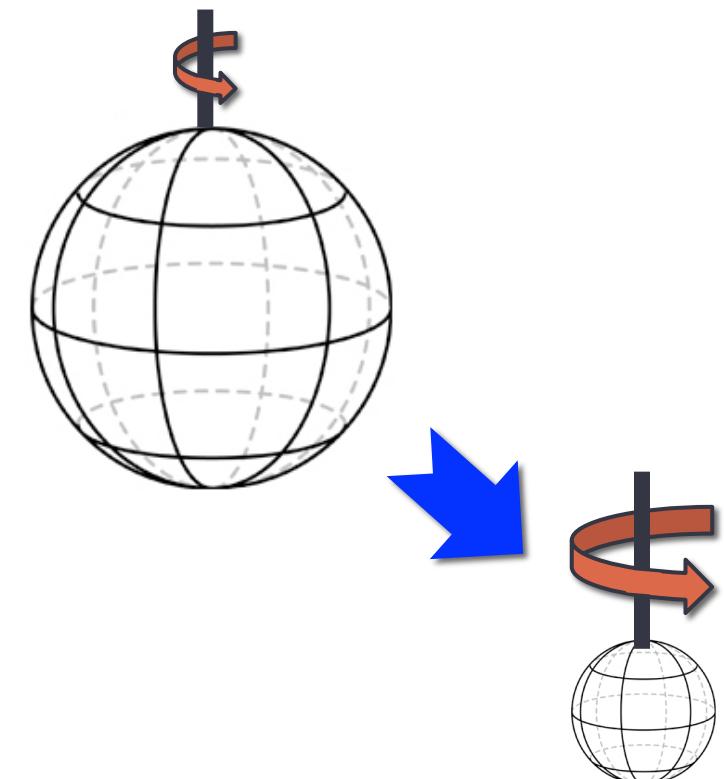
What role does moist convection play in the momentum budget of the Hadley cell?

How strongly does the momentum budget constrain the strength of the Hadley circulation?

Simultaneously resolving moist convection and planetary-scale motions is computationally infeasible (for most of us)

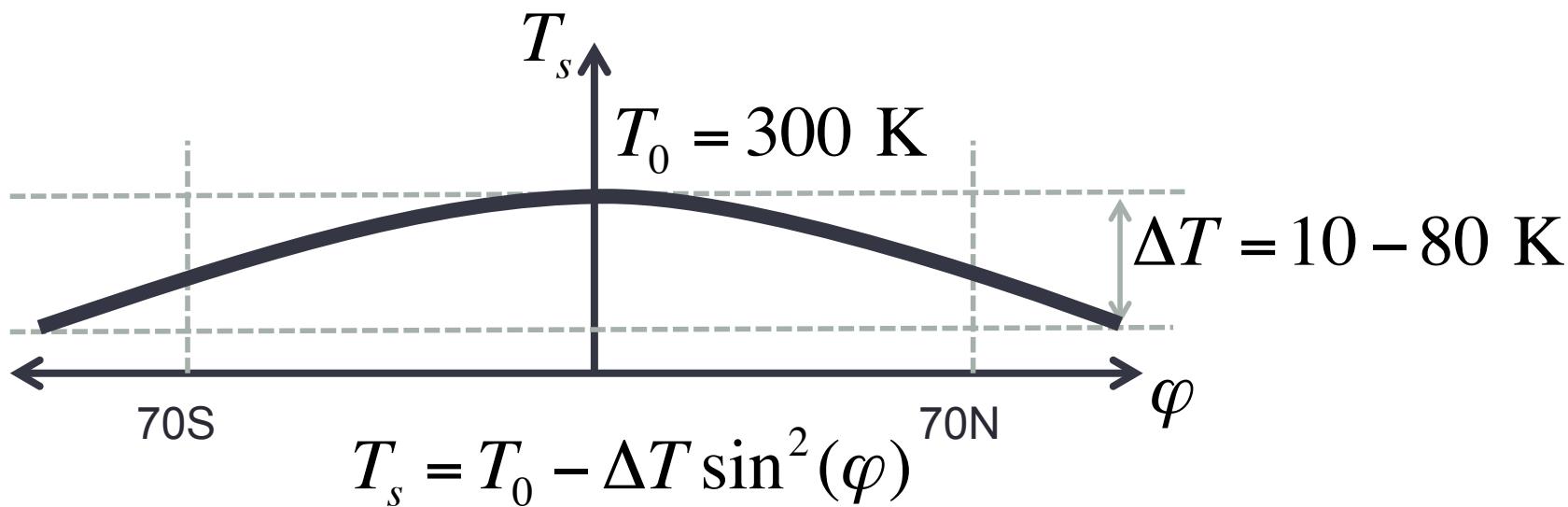
Simultaneously resolving moist convection and planetary-scale motions is computationally infeasible (for most of us)

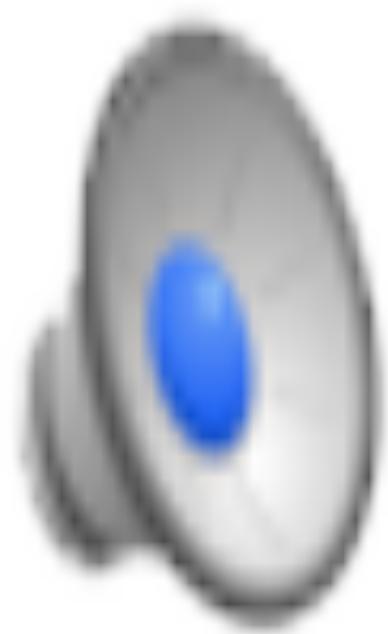
- Use the diabatic acceleration and rescaling (DARE) approach (Kuang, et al., 2005)
- Solves analogous physical system
- Reduces scale-separation between convection and planetary-scale flows by factor $\alpha = 10$



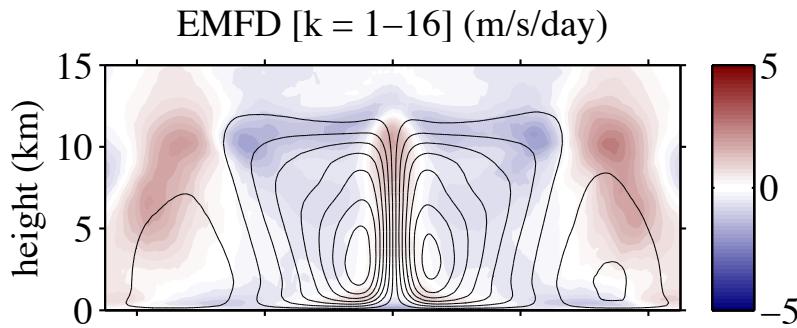
DARE simulations with SAM

- Equatorial beta-plane 70S-70N, 0-140E
- 40 km resolution with DARE factor of 10
- Convection “sees” 4 km resolution (Kuang et. al, 2005)
- Idealized “radiation” scheme: $Q = -\frac{T - 220 \text{ K}}{50 \text{ days}}$
- Fixed SST distribution:

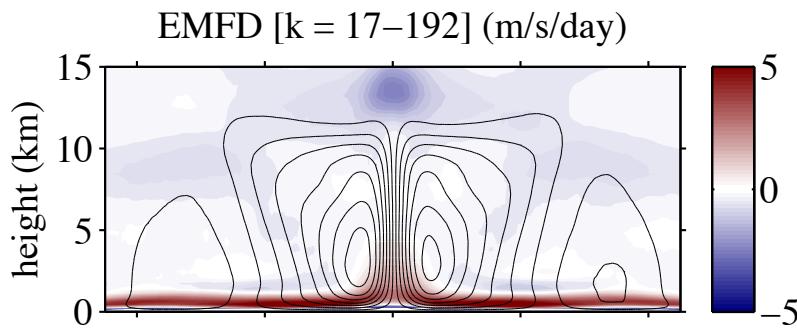




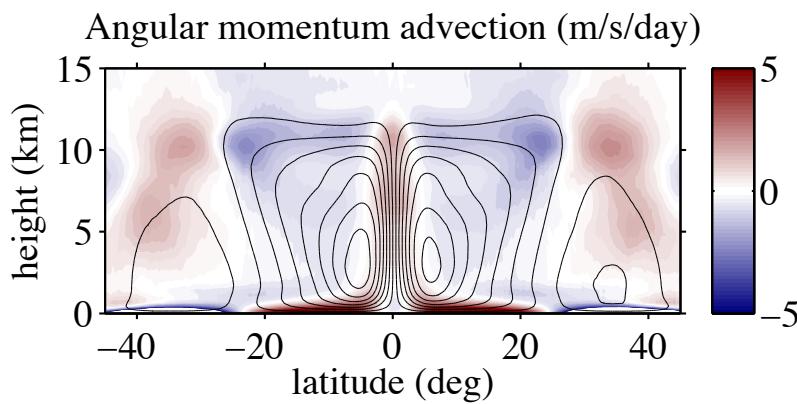
Momentum transport dominated by large-scale eddies



Large-scale eddy-momentum flux divergence



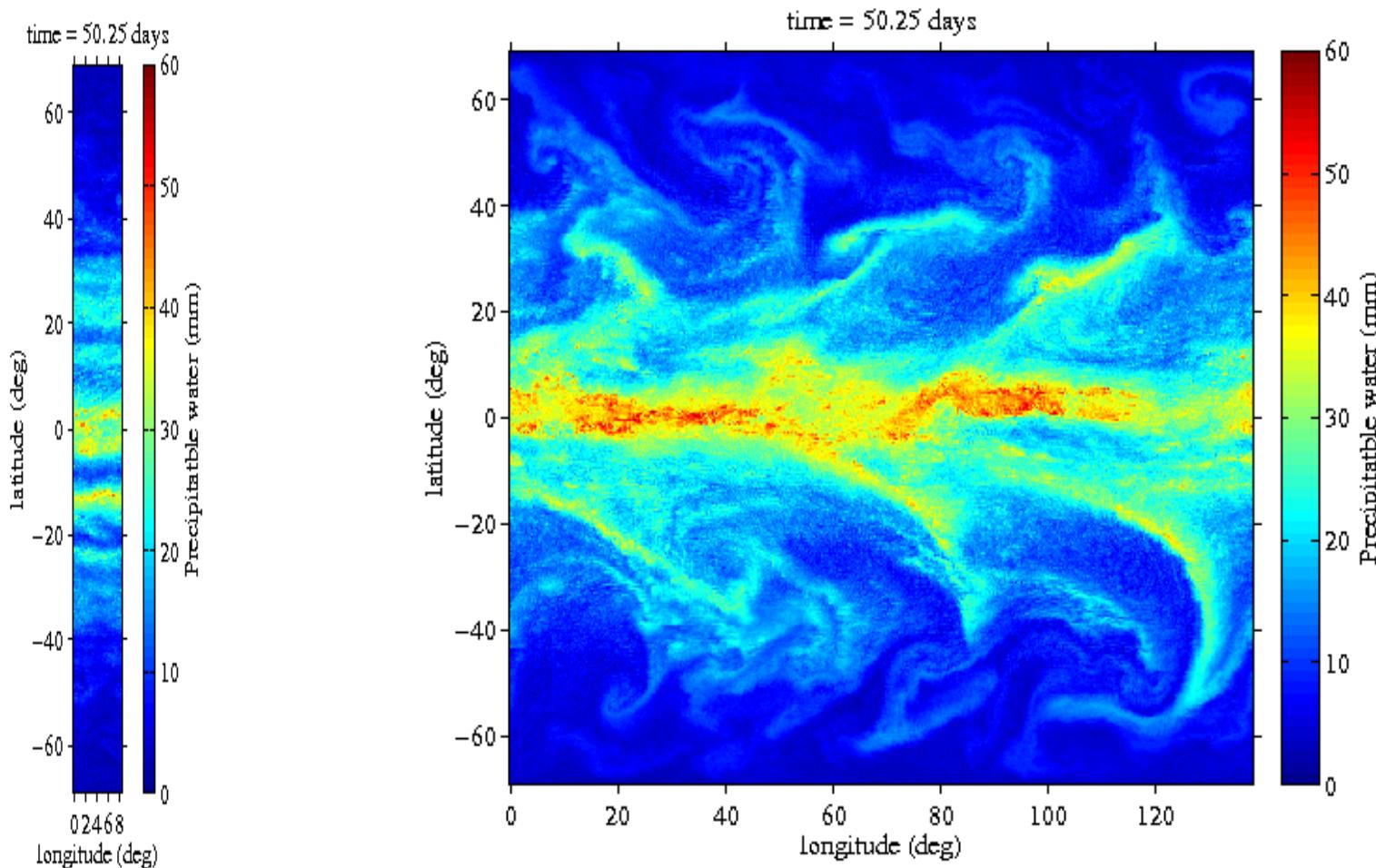
Small-scale eddy-momentum flux divergence



Mean angular momentum advection

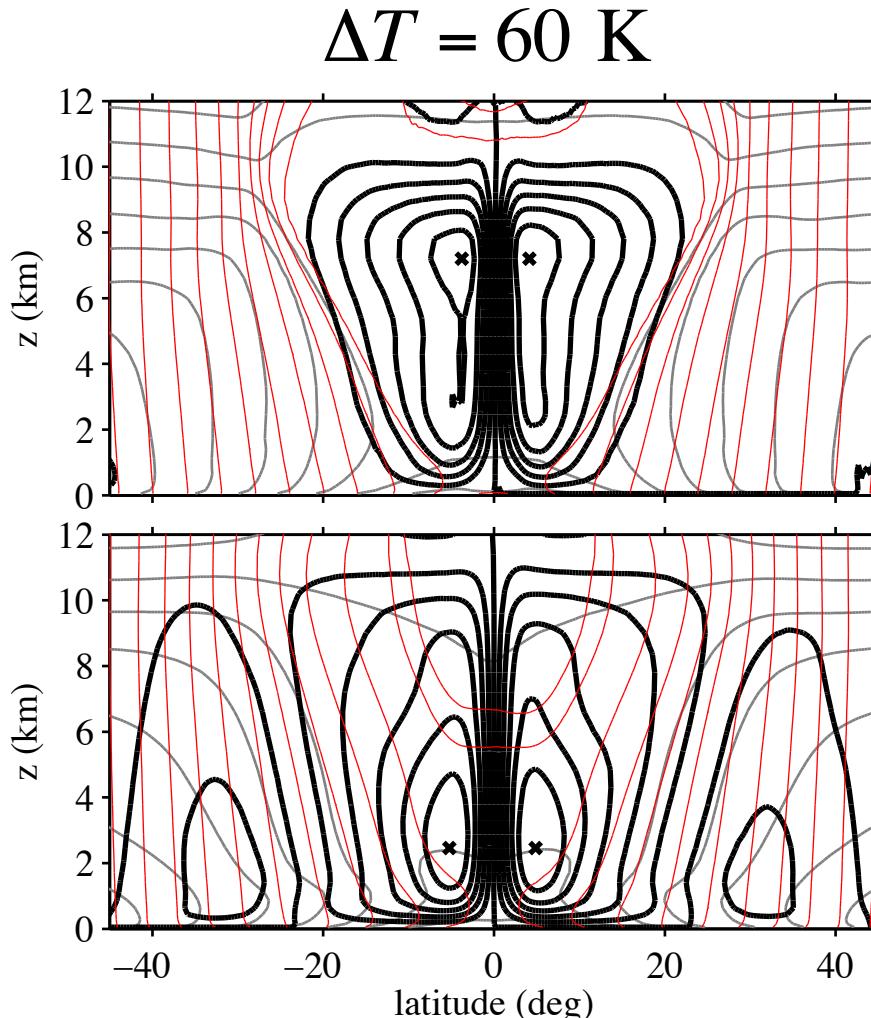
$$\bar{v} \frac{\partial M}{\partial y} + \bar{w} \frac{\partial M}{\partial z}$$

Use narrow domain to remove effects of large-scale eddies



Eddies strongly affect Hadley cell characteristics

Narrow domain

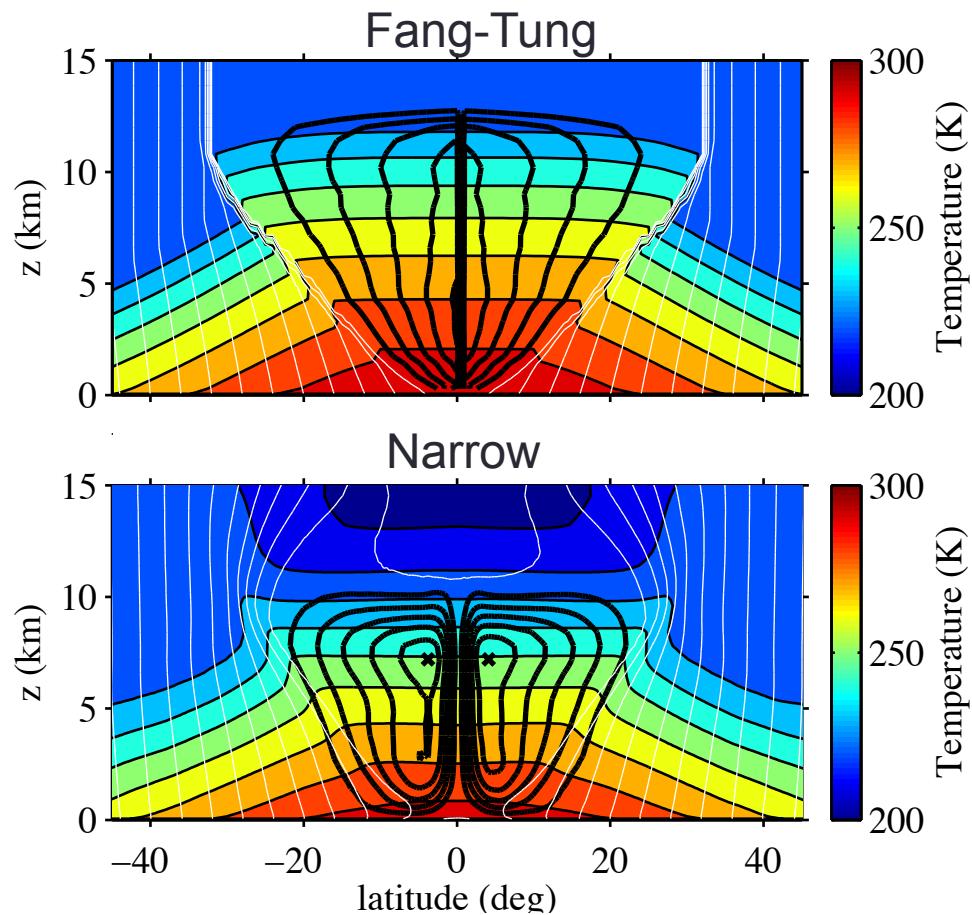


- Narrow Hadley cell conserves angular momentum (cumulus momentum transport weak)
- Narrow Hadley cell has slanted descending branch
- No Ferrel cell in narrow case

Narrow Hadley cell resembles axisymmetric model of Fang & Tung (1996)

Fang & Tung (1996):

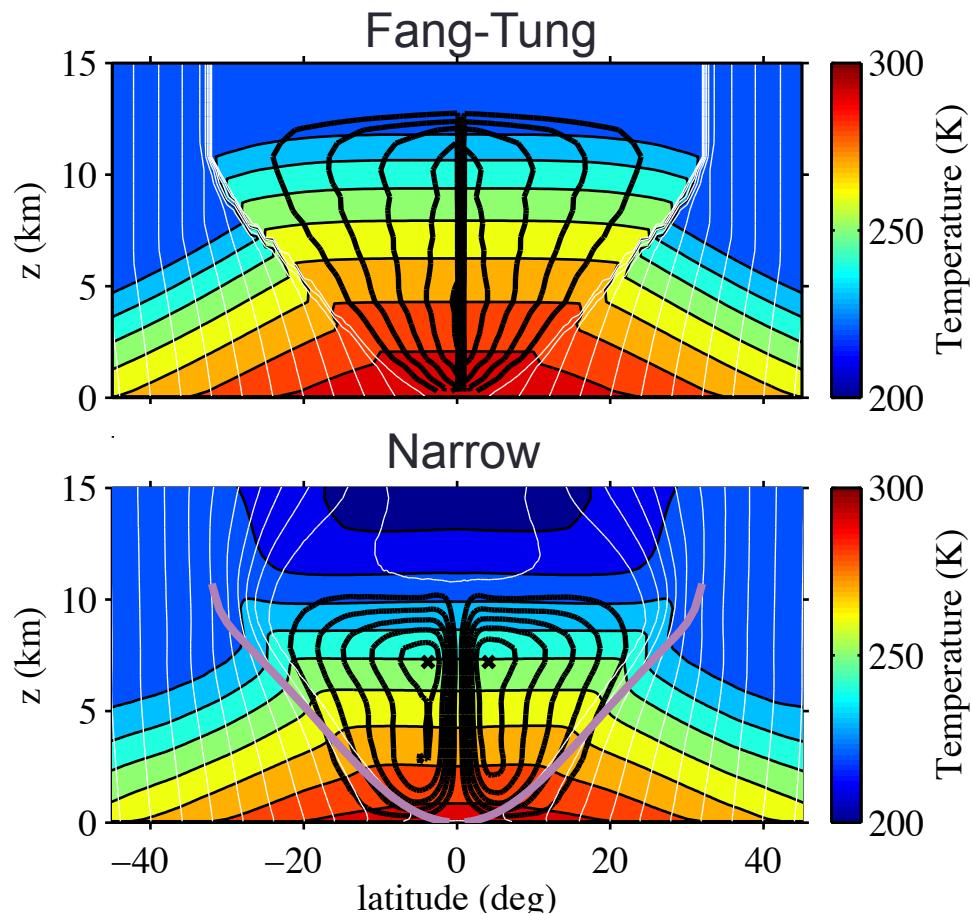
- Fixed-SST, axisymmetric circulation
- Angular momentum homogenized within Hadley cell
- No horizontal temperature gradients within Hadley cell
- Slanted descending branch



Narrow Hadley cell resembles axisymmetric model of Fang & Tung (1996)

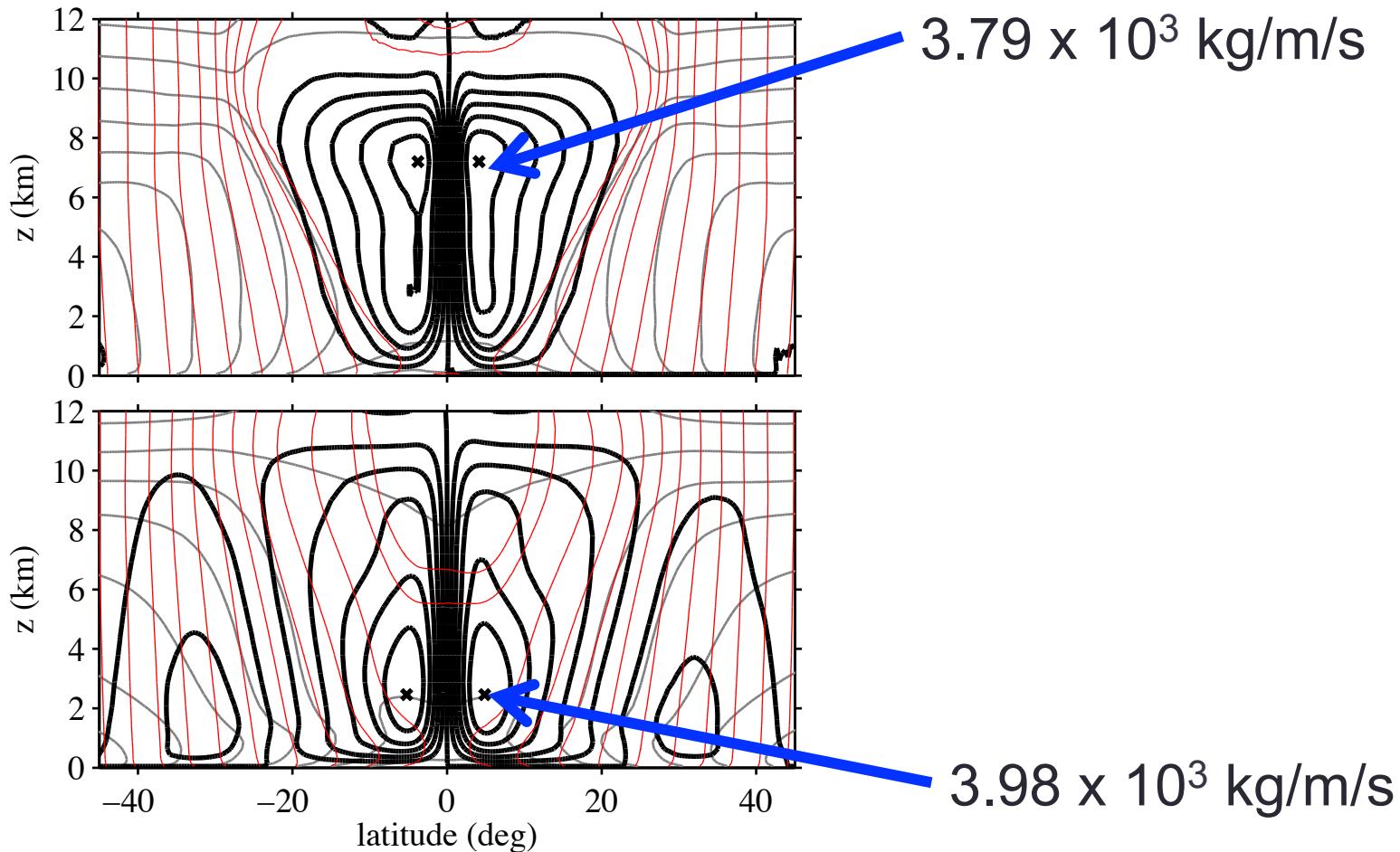
Fang & Tung (1996):

- Fixed-SST, axisymmetric circulation
- Angular momentum homogenized within Hadley cell
- No horizontal temperature gradients within Hadley cell
- Slanted descending branch

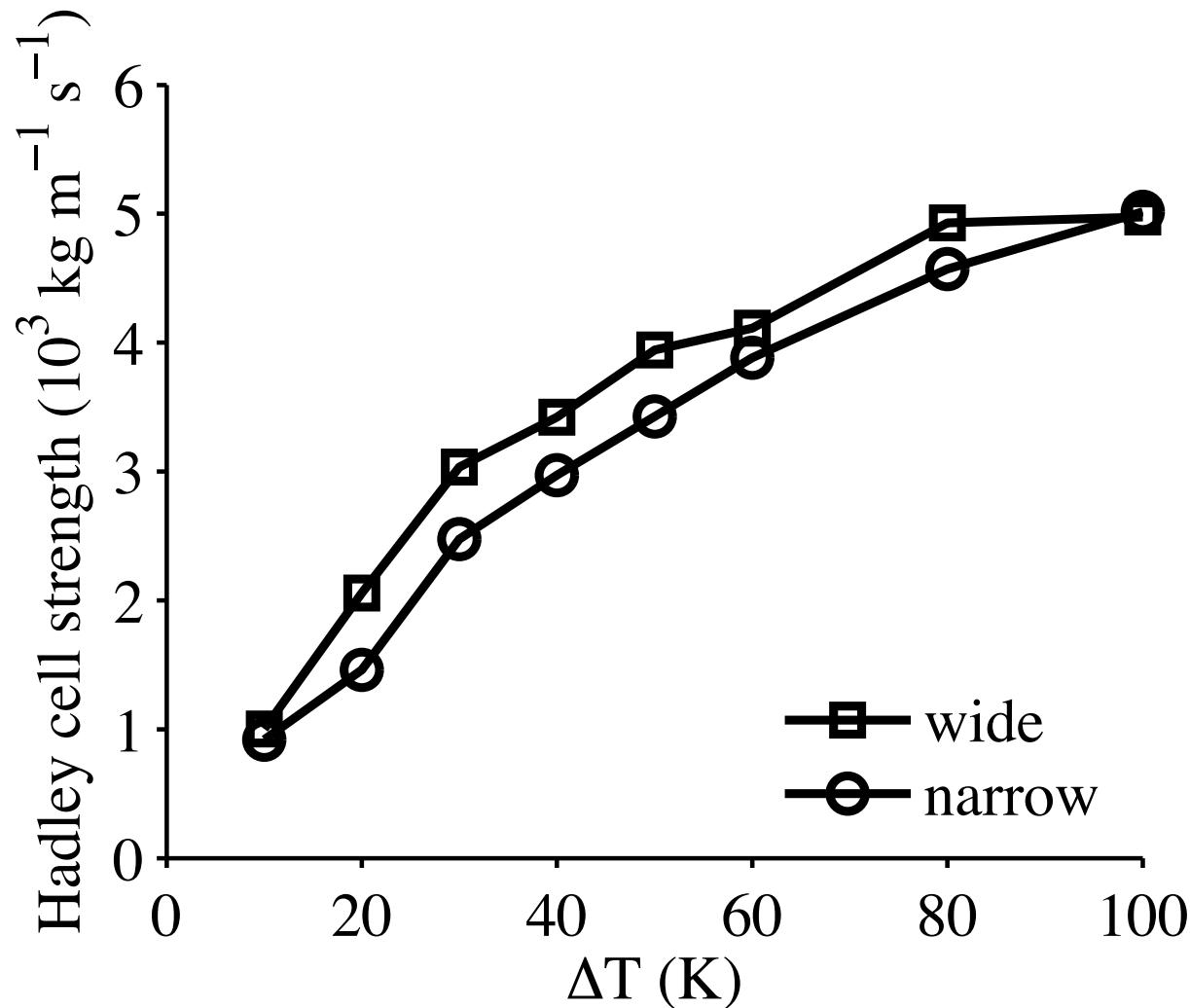


Hadley cell strength (max streamfunction) similar in narrow and wide simulations

Narrow
domain



HC strength scales similarly with and without baroclinic eddies



Simple thermodynamic balance holds in descending branch

- Steady-state thermodynamic equation:

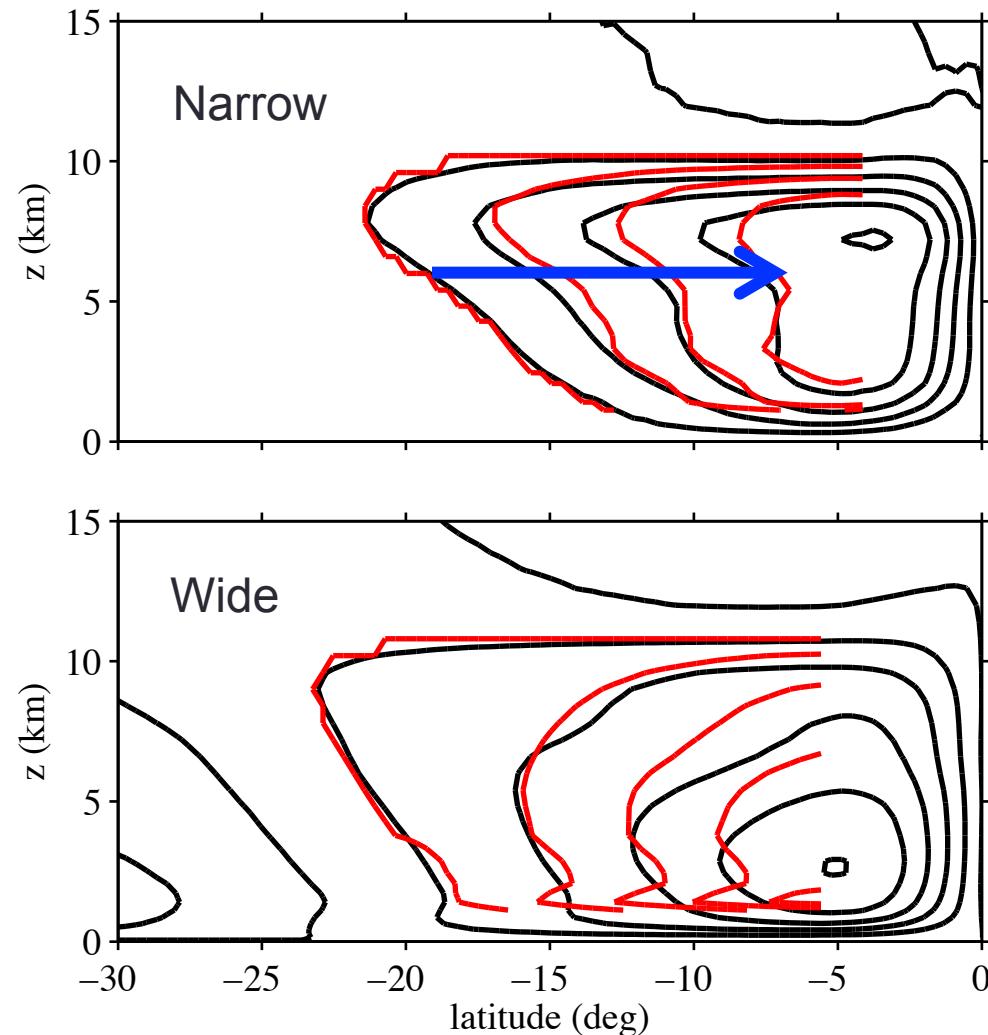
$$\bar{v} \frac{\partial \bar{\theta}}{\partial y} + \bar{w} \frac{\partial \bar{\theta}}{\partial z} = \frac{\bar{Q}_{net}}{c_p \pi} - \frac{1}{\rho} \frac{\partial \rho \bar{v}' \bar{\theta}'}{\partial y} - \frac{1}{\rho} \frac{\partial \rho \bar{w}' \bar{\theta}'}{\partial z}$$

- weak eddies
- weak horizontal temperature gradients

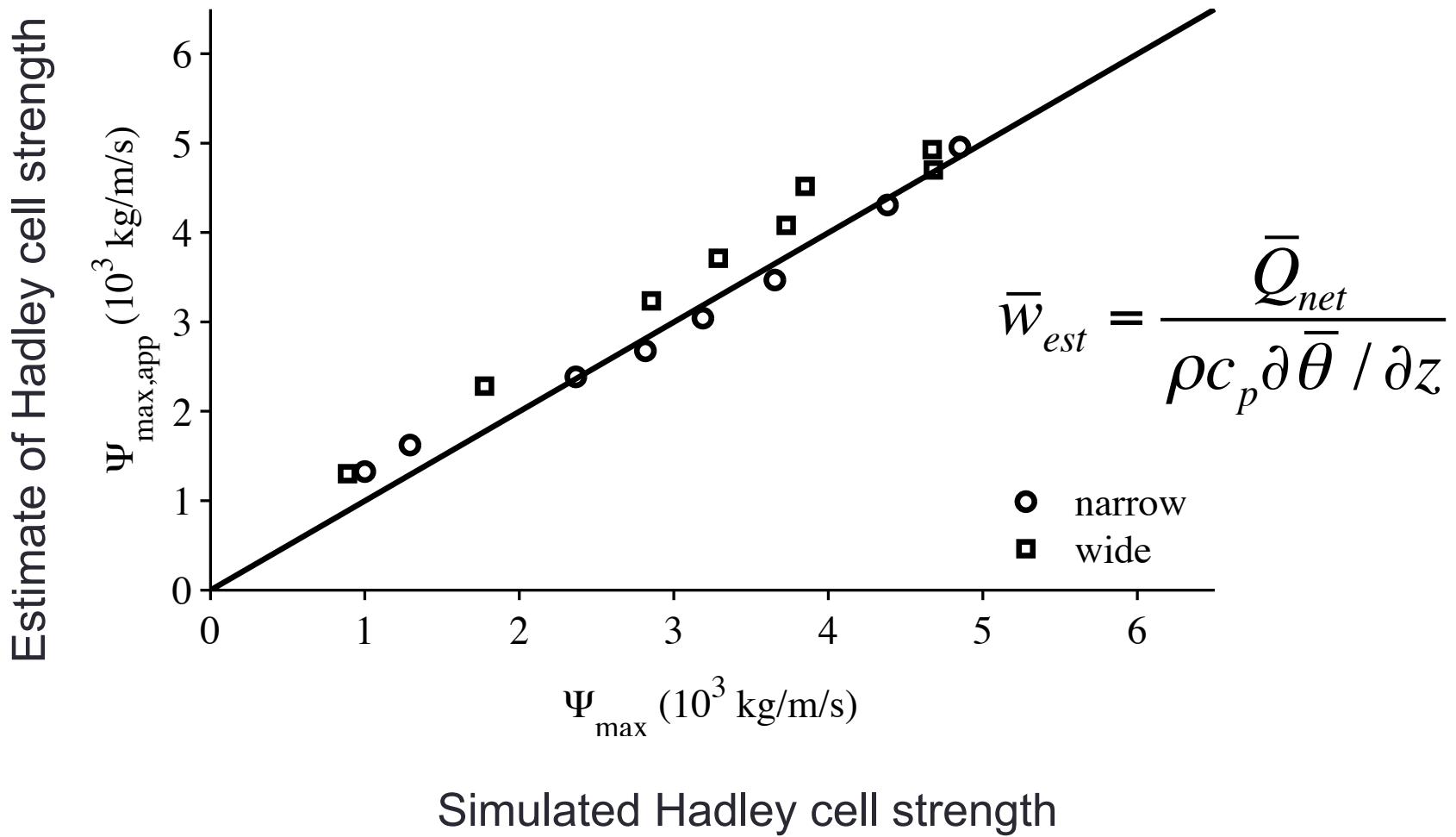
Use thermodynamic balance to calculate streamfunction

$$\bar{w}_{est} \frac{\partial \bar{\theta}}{\partial z} = \frac{\bar{Q}_{net}}{c_p \pi}$$

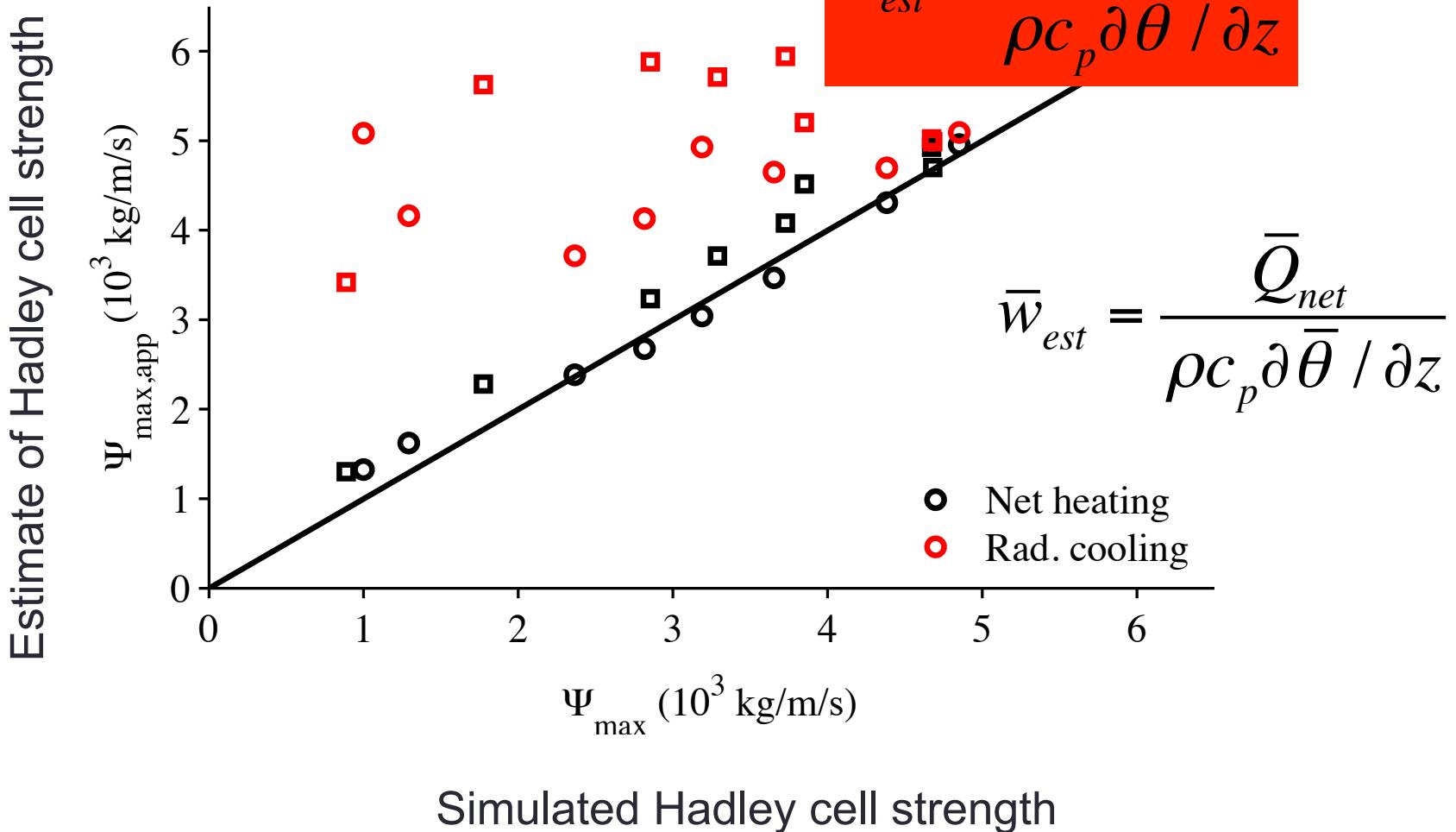
$$\Psi_{est} = \int \rho \bar{w}_{est} \ dy$$



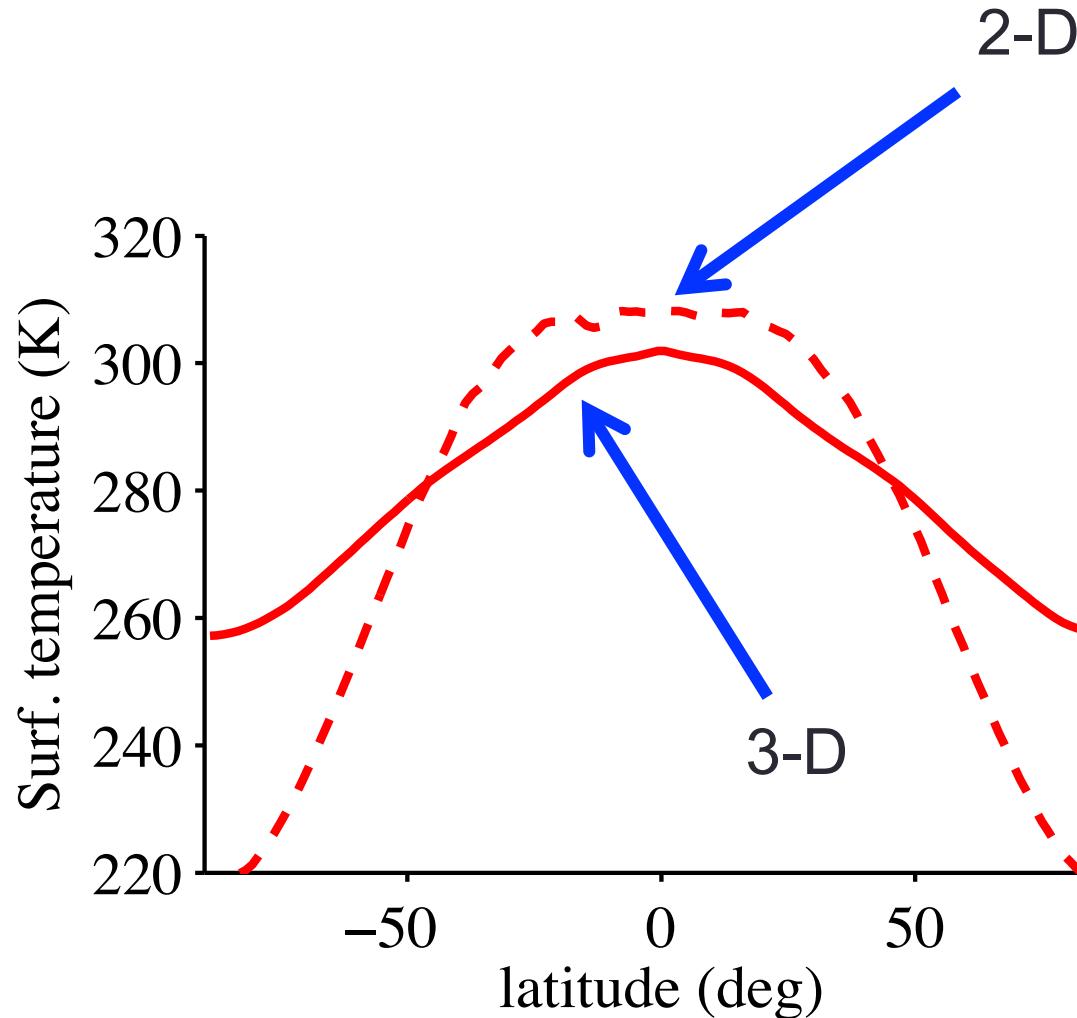
Net heating in descending branch provides good estimate of Hadley cell strength



Convection in descending branch important for $\Delta T < 80$ K



2-D versus 3-D GCM simulations with slab-ocean



Conclusions

- What role does moist convection play in the momentum budget of the Hadley cell?

Not a first order effect

- How strongly does the momentum budget constrain the strength of the Hadley circulation?

In SAM simulations HC strength insensitive to presence of eddies; thermodynamic balance holds

But our simulations do not include a closed energy budget...