Thermodynamic and dynamic controls on the Hadley circulation

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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)
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- 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:
  \[ T_s = T_0 - \Delta T \sin^2(\varphi) \]
Momentum transport dominated by large-scale eddies

Large-scale eddy-momentum flux divergence

Small-scale eddy-momentum flux divergence

Mean angular momentum advection

\[ \overline{v} \frac{\partial M}{\partial y} + \overline{w} \frac{\partial M}{\partial z} \]
Use narrow domain to remove effects of large-scale eddies
Eddies strongly affect Hadley cell characteristics

\[ \Delta T = 60 \text{ K} \]

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

See also Satoh, et. al (1995)
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
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Hadley cell strength (max streamfunction) similar in narrow and wide simulations

Narrow domain

Wide domain

3.79 x 10^3 kg/m/s

3.98 x 10^3 kg/m/s
HC strength scales similarly with and without baroclinic eddies

![Graph showing Hadley cell strength vs. ΔT (K)]
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

\[
\overline{W}_{est} \frac{\partial \bar{\theta}}{\partial z} = \frac{\overline{Q}_{net}}{c_p \pi}
\]

\[
\Psi_{est} = \int \rho \overline{w}_{est} \ dy
\]
Net heating in descending branch provides good estimate of Hadley cell strength

\[ \Psi_{\text{max},\text{app}} (10^3 \text{ kg/m/s}) \]

Simulated Hadley cell strength

\[ \overline{W}_{est} = \frac{\overline{Q}_{\text{net}}}{\rho c_p \frac{\partial \theta}{\partial z}} \]

Estimate of Hadley cell strength

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

Estimate of Hadley cell strength

Simulated Hadley cell strength

\[
\Psi_{\text{max,app}} = 10^3 \text{ kg/m/s}
\]

\[
\Psi_{\text{max}} = \frac{Q_{\text{net}}}{\rho c_p \partial \bar{\theta} / \partial z}
\]

\[
\bar{W}_{\text{est}} = \frac{Q_{\text{rad}}}{\rho c_p \partial \bar{\theta} / \partial z}
\]
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…