Investigating the Hadley Cell and eddies with varying sea surface temperature gradients

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Background & Motivation

- The Hadley Cell (HC) is a pair of thermally direct cells that transports heat and momentum poleward from the tropics (Peixoto and Oort, 1992). It explains the tropical easterlies and subtropical westerlies.

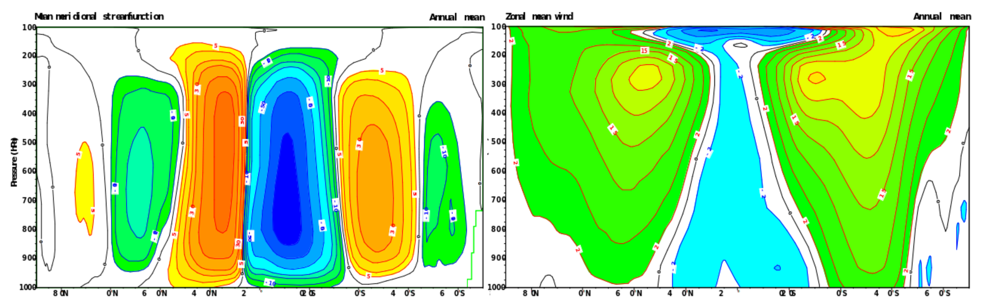

Figure 1:Annual mean mass streamfunction and zonal wind.

- Midlatitude baroclinic eddies influence both the strength and extent of the HC (Walker and Schneider, 2006; Schneider, 2006; Korty and Schneider, 2008).

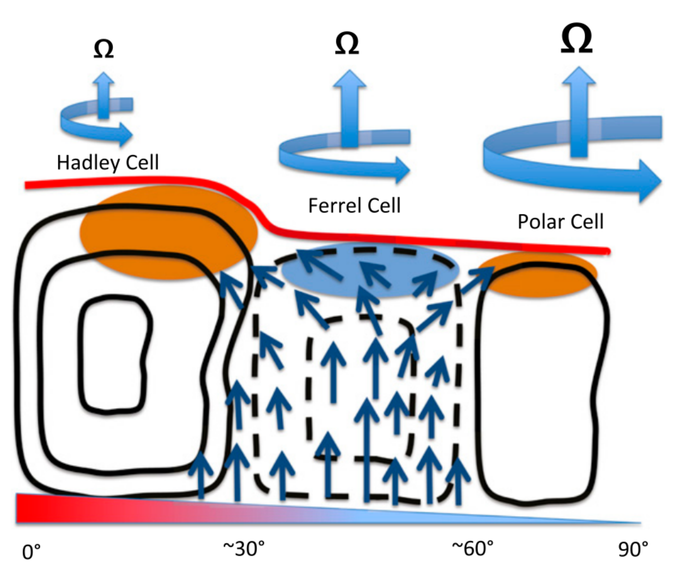

Figure 2:Adapted from Levine and Schneider (2015).

- But an understanding of the tropical wave influence has been lacking. In the zonal mean, regions of convergence and divergence associated with these waves tend to cancel each other, but the precipitation survives since it is a positive-only quantity (Horinouchi, 2012). Tropical waves can modify the precipitation and influence HC ascent through the associated latent heating.

Our primary motivation is to highlight the role of tropical waves relative to extratropical waves in shaping the HC.

Model and Experiment Setup

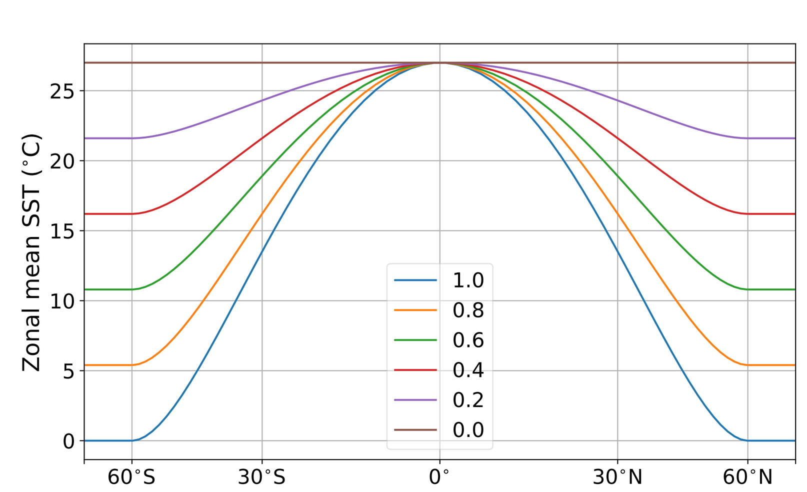

Figure 3:Zonal mean SST profiles used to force the atmosphere. Legend shows α values that indicates the gradient of SST.

- Aquaplanet (CAM6, CESMv2.1.3) with fixed SSTs
- Spectral core at T42 horizontal resolution and 32 vertical levels
- Uniform solar flux, no seasonal cycle and no diurnal cycle

The circulation develops purely as a response to the imposed SST forcing.

Zonal mean tropical circulation

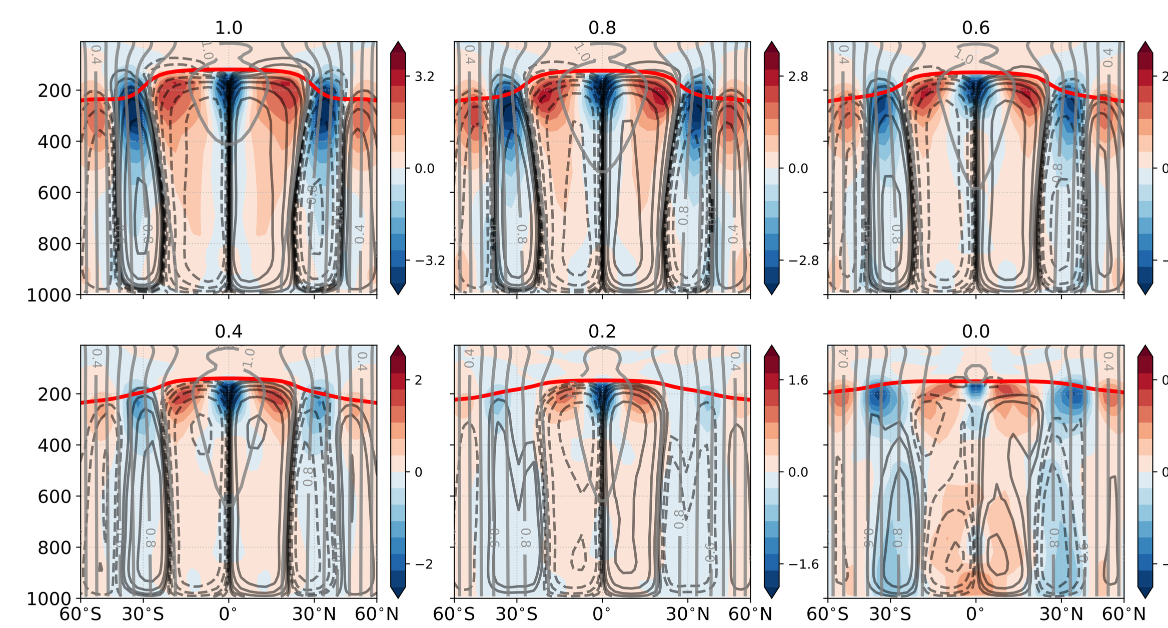

Figure 4:Streamfunction (contours), eddy momentum flux divergence (colours), angular momentum (gray contours).

- Conventional HCs develop in all simulations.
- For non-zero SST gradients, organised deep convection occurs preferentially over warmer SSTs.
- For larger SST gradients, contours of constant angular momentum appear to be advected by the upper tropospheric flow.
- Midlatitude baroclinic eddies diverge momentum away from the HC edge in the subtropics and transport heat polewards (see EP flux in Fig. 7).

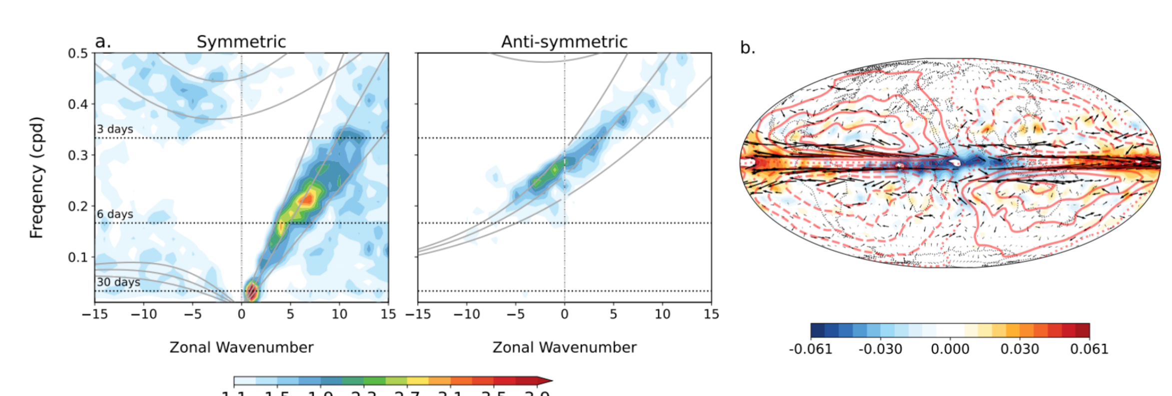

Figure 5:(a) Wheeler Kiladis spectra and (b) MJO composites of pressure velocity at 500 mbar (colours) and upper level streamfunction following Adames and Wallace (2014) for the α=0.0 simulation.

- For flat SST, equatorial convergence associated with tropical waves facilitates the HC ascent.
- Presence of equatorial Kelvin and Mixed Rossby-Gravity waves along with a wave-1 MJO-like mode.

$$f(1-Ro)[\overline{v}] = (\cos^2\phi)^{-1}\partial_y[\overline{u'v'}\cos^2\phi]$$

$$Ro = \begin{cases} 1, & \text{thermally driven} \\ 0, & \text{eddy-driven} \end{cases}$$

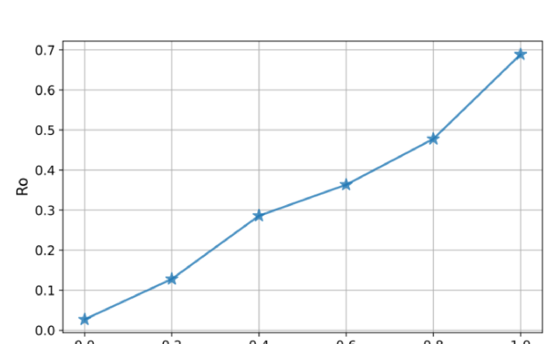

Figure 6:Vorticity based bulk Rossby number analysis of Walker and Schneider (2006).

- For progressively flatter SSTs, the HC moves from a regime that's thermally and eddy driven to one that's completely eddy driven.
- Angular momentum contours become more vertical similar to those in the midlatitudes.
- Double maxima structure in eddy momentum flux for flat SST.
- HC strength is an order of magnitude weaker in the α=0.0 simulation compared to α=1.0.

Mean wind, thermal structure and waves

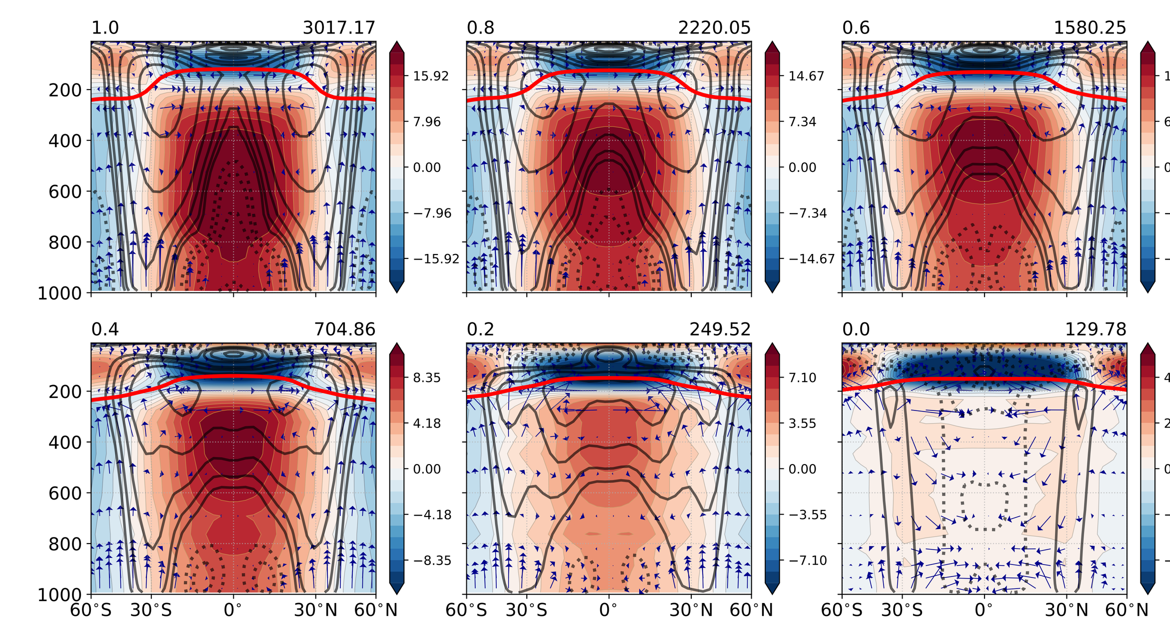

Figure 7:Zonal wind (contours), Eliassen Palm (EP) flux (quivers) and meridionally anomalous temperature (colours) .

- Zonal wind structure weakens and the subtropical and eddy-driven jets begin to separate at $\alpha=0.4$. The subtropical jet is absent for flat SST.
- The tropics remain warmer than the poles except for the flat SST case where the upper subtropics are anomalously warm. The tropopause flattens with weakening SST gradients. UTLS is cooler over the tropics than the poles.
- Wave propagation changes with weakening SST gradients. For small α, waves generated near the surface remain confined to the lower troposphere. Upper level baroclinicity generates waves that cause poleward transport of momentum.

Residual circulation & the TEM

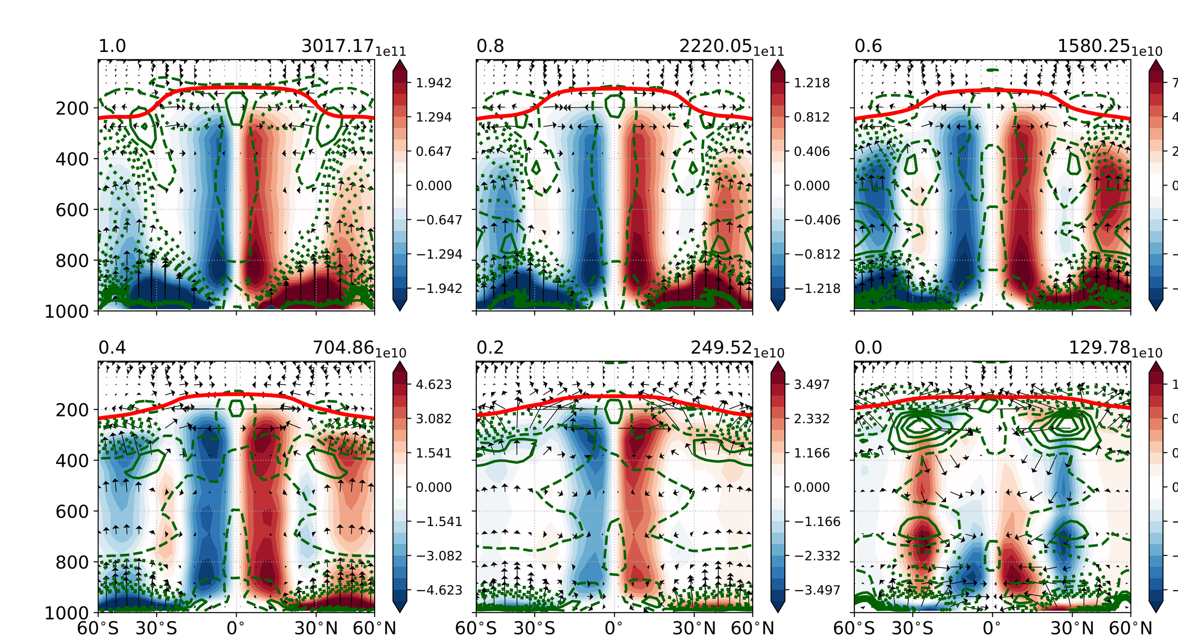

Figure 8:Residual streamfunction (colours), EP flux divergence (contours), EP flux (quivers).

Steady state frictionless zonal momentum equation in TEM form reads,

$$-fv^* \approx \nabla \cdot \vec{F}$$

(Edmon et al., 1980)

- For conventional SST, the residual circulation shows a direct hemisphere wide cell (Holton and Hakim, 2012).
- In the extratropical lower troposphere, the residual circulation and eddy fluxes are strongly coupled as the Coriolis torque on the residual circulation balances the EP flux convergence (Birner, 2010).
- For flat SST, equatorward v^* is induced by isolated centers of EP flux divergence in the subtropical upper troposphere.
- Unlike those in the present-day Earth, the Ferrel cells observed here are not artefacts of the Eulerian mean.

Summary

- We have conducted aquaplanet simulations with uniform solar flux and fixed orbital parameters to examine the influence of tropical and extra-tropical waves on the Hadley circulation. Apart from the SST boundary forcing, there are no imposed thermal gradients and the circulation develops purely as a response to the SSTs.
- Thermally direct overturning cells are observed in all simulations.
- The HC transitions from a thermally and edd-driven regime to one that is completely eddy-driven.
- Midlatitude baroclinic waves transport heat and angular momentum polewards from the subtropical HC edge.
- Tropical waves modulate the HC ascent through their influence on precipitation and the latent heating field. In the absence of thermal gradients, equatorial convergence by these waves is sufficient to generate a deep overturning circulation.
- As the imposed SST gradient is decreased, conventional baroclinic waves become weak and remain confined to the lower troposphere. Upper level baroclinicity becomes more important. The extratropical tropopause rises and convection becomes more important in setting the tropopause height.
- Isolated centers of EP flux divergence form in the subtropical upper troposphere that force a thermally indirect circulation and highlights the role played by convection in determining the extra-tropical dynamics when thermal gradients are weak.

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