Disconnect Between Hadley Cell and Subtropical Jet Variability and Response to Increased CO$_2$

Molly Menzel$^1$, Darryn Waugh$^{1,2}$, Kevin Grise$^3$

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Subtropical Jet and Hadley Cell Relationship

\[ \bar{u} = \Omega a \frac{(\sin \varphi)^2}{\cos \varphi} \]

\[ \frac{\partial u}{\partial z} \propto \frac{\partial T}{\partial y} \]
Subtropical Jet and Hadley Cell Relationship

By our current understanding of atmospheric general circulation, the subtropical jet’s location should shift with the Hadley cell edge...

... the reanalyses and models do not support this.
-Waugh et al. 2018
-Solomon et al. 2016
-Davis and Birner 2017
Subtropical Jet and Hadley Cell Relationship

By our current understanding of atmospheric general circulation, the subtropical jet’s location should shift with the Hadley cell edge...

... the reanalyses and models do not support this.
- Waugh et al. 2018
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why is this?
Subtropical Jet and Hadley Cell Relationship

1. What is the natural, interannual relationship between the HC and STJ?

2. How do the STJ and HC respond to $4x\text{CO}_2$ forcing?

3. What are the physical processes that dictate HC and STJ behavior?
Metrics
Metrics

Hadley Cell

“PSI500”

\[ \phi_{HC} = \phi(\psi_{500\ hPa} = 0) \]

\[ \psi_{HC} = \max(\psi_{500\ hPa}) \]
**Metrics**

**Hadley Cell**

“PSI500”

\[ \varphi_{HC} = \varphi (\psi_{500 \, hPa} = 0) \]

\[ \psi_{HC} = \max (\psi_{500 \, hPa}) \]

**Eddy-Driven Jet (EDJ)**

\[ \varphi_{EDJ} = \varphi (\max (u_{850 \, hPa})) \]

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Metrics

Hadley Cell

“PSI500”

\[ \varphi_{HC} = \varphi(\psi_{500\,hPa} = 0) \]
\[ \psi_{HC} = \max(\psi_{500\,hPa}) \]

Eddy-Driven Jet (EDJ)

\[ \varphi_{EDJ} = \varphi(\max(u_{850\,hPa})) \]

Subtropical Jet (STJ)

\[ \varphi_{STJ} = \varphi(\max(\Delta u)) \]
\[ u_{STJ} = \Delta u(\varphi_{STJ}) \]
\[ \Delta u = u_{100-400\,hPa} - u_{850\,hPa} \]
CMIP5 Data

Coupled Model Intercomparison Project (Phase 5)

Output from coupled simulations

\textit{piControl}

Control with pre-industrial levels of CO2
CMIP5 Data

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Control with pre-industrial levels of CO2

\textit{abrupt4xCO2}

Abrupt quadrupling of CO2, held fixed
CMIP5 Data

Coupled Model Intercomparison Project (Phase 5)

Output from coupled simulations

*piControl*

Control with pre-industrial levels of CO2

*abrupt4xCO2*

Abrupt quadrupling of CO2, held fixed
CMIP5: Interannual

**HC**
- Expands, weakens

**EDJ**
- Shifts poleward, strengthens

**STJ**
- Shifts poleward, weakens

\[
\sum_t u(\phi HC > 2\sigma) \quad - \quad \sum_t u(\phi HC < 2\sigma)
\]

Menzel et al. 2019
CMIP5: Interannual

HC
- Expands, weakens

EDJ
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STJ
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narrow tropical cooling

Expanded HC
- contracted HC

\[ \sum_t u(\phiHC > 2\sigma) \]

\[ - \sum_t u(\phiHC < 2\sigma) \]

Menzel et al. 2019
### CMIP5: Interannual

<table>
<thead>
<tr>
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<th>Southern Hemisphere</th>
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<td>$\phi_{HC}$</td>
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Menzel et al. 2019
## CMIP5: Interannual

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<td></td>
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<td>$\phi_{maxSTJ}$</td>
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**Natural Variability**

- **HC Location**: More poleward HC, weaker STJ
- **STJ Strength**: More poleward HC, weaker STJ

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CMIP5: Response

HC
- Expands, weakens

EDJ
- Shifts poleward, strengthens

STJ
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Menzel et al. 2019
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broad warming
**CMIP5: CO$_2$ Response**

<table>
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<tr>
<th>HC Location</th>
<th>STJ Strength</th>
<th>Natural Variability</th>
<th>Response to 4xCO$_2$</th>
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<td>+</td>
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More poleward HC, weaker STJ  
More poleward HC, stronger STJ
Warming Width
Warming Width: CMIP5

Similar patterns shown in
- Lu et al. 2008
- Sun et al. 2013
- Tandon et al. 2013

Menzel et al. 2019
Warming Width

- Lu et al. 2008
- Sun et al. 2013
- Tandon et al. 2013

Narrow tropical warming (ENSO)

more narrow HC
Warming Width

- Lu et al. 2008
- Sun et al. 2013
- Tandon et al. 2013

Narrow tropical warming (ENSO)

Broad warming (global forcing)

more narrow HC

wider HC

Lu et al. 2008
Warming Width

- Lu et al. 2008
- Sun et al. 2013
- Tandon et al. 2013

Narrow tropical warming (ENSO)

Broad warming (global forcing)

more narrow HC

stronger STJ

wider HC
Warming Metrics

$\Delta$Temperature $[{ }^\circ \text{C}]$
Warming Metrics

**Warming Strength**

\[ \Delta T_{\text{max}} = \text{max}(\Delta T_{30S-30N}) \]

**Warming Width**

\[ \Delta \phi_T = \Delta \phi_{10\% \Delta T_{\text{max}}} \]

![Diagram](image-url)
Warming Width: Response

CMIP5

HC  EDJ  STJ

ΔφT

Poleward Shift [°]

Δ [m s⁻¹, 10¹⁰ kg s⁻¹]

0  20  40  60  80
0  20  40  60  80
Warming Width: Response

CMIP5

Narrow tropical warming:
HC contracts, STJ strengthens
Warming Width: Response

CMIP5

Narrow tropical warming:
HC contracts, STJ strengthens

Broad global warming:
HC expands, STJ strengthens
Warming Width: Response

How consistent is this response?

Comparing with idealized atmospheric models:

- GFDL dry dynamical core
  Temperature perturbation as in Sun et al. 2013

- GFDL dry core with convection parameter
  Data from Tandon et al. 2013

- Aquaplanet with specified SSTs
  Data from Watt-Meyer and Frierson 2019
Warming Width: Response

Dry Core (with convection)

Tandon et al. (2013)

Aquaplanet

Watt-Meyer & Frierson (2019)

CMIP5

Idealized Complex

$\Delta$ Strength [$\text{m s}^{-1}, 10^{10} \text{kg s}^{-1}$]

$\Delta \phi_T$

$\Delta$ Poleward Shift [°]

$\Delta \phi_T$
Conclusions
Key Takeaways

1. The interannual relationship between HC edge and STJ strength is the opposite sign as the response to increased atmospheric CO$_2$
Key Takeaways

1. The interannual relationship between HC edge and STJ strength is the opposite sign as the response to increased atmospheric CO$_2$

2. The STJ always strengthens given a warming while the HC’s movement is dependent on the width of warming

<table>
<thead>
<tr>
<th>$\phi_{HC}$ maxSTJ</th>
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<th>Response to 4xCO$_2$</th>
<th>$\tau$</th>
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<tr>
<td>$\phi_{HC}$ Poleward shift</td>
<td>7</td>
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<tr>
<td>$u_{STJ}$ strengthening</td>
<td>40</td>
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Future Work

What are the physical processes that dictate HC and STJ behavior?

MODEL: Aquaplanet Simulations (prescribed SSTs)

1. How are the STJ and HC sensitive to meridional temperature gradients?
   1st Set of Runs: Tropical warming with various widths
   \((5°, 15°, 25°, 35°, 45°)\)
Future Work

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MODEL: Aquaplanet Simulations (prescribed SSTs)

1. How are the STJ and HC sensitive to meridional temperature gradients?
   1\textsuperscript{st} Set of Runs: Tropical warming with various widths
   \((5^\circ, 15^\circ, 25^\circ, 35^\circ, 45^\circ)\)

2. How are the STJ and HC sensitive to changes in midlatitude eddies?
   2\textsuperscript{nd} Set of Runs: Zonally symmetric tropical warming
   (no waves)
   3\textsuperscript{rd} Set of Runs: Polar cooling
   \((60^\circ-90^\circ)\)
Future Work

What are the physical processes that dictate HC and STJ behavior?

MODEL: Aquaplanet Simulations (prescribed SSTs)

1. How are the STJ and HC sensitive to meridional temperature gradients?
   Analysis: Evaluate response as a function of warming width

2. How are the STJ and HC sensitive to changes in midlatitude eddies?
   Analysis: decomposition of momentum budget

\[
\frac{\partial u}{\partial t} = (f + \bar{\zeta}) \bar{v} - \frac{1}{a \cos^2 \phi} \frac{\partial}{\partial \phi} (\bar{u'} \bar{v'} \cos^2 \phi)
\]
Future Work

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Extra Slides
## CMIP5: Interannual Correlations

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<tr>
<td>(\phi_{HC})</td>
<td>-0.4</td>
<td>0</td>
<td>-0.31</td>
<td>-0.23*</td>
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<tr>
<td>maxHC</td>
<td>(0.11)</td>
<td>(0.12)</td>
<td>(0.16)</td>
<td>(0.12)</td>
</tr>
<tr>
<td>(\phi_{HC})</td>
<td>0.52*</td>
<td>0.72*</td>
<td>0.46*</td>
<td>0.24</td>
</tr>
<tr>
<td>(\phi_{EDJ})</td>
<td>(0.14)</td>
<td>(0.06)</td>
<td>(0.14)</td>
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Menzel et al. 2019
CMIP5: CO\textsubscript{2} Response

Time series of metrics’ response to 4xCO\textsubscript{2}

<table>
<thead>
<tr>
<th>Shift/Change</th>
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<tbody>
<tr>
<td>φ\textsubscript{HC}</td>
<td>poleward</td>
</tr>
<tr>
<td>φ\textsubscript{STJ}</td>
<td>slight poleward</td>
</tr>
<tr>
<td>u\textsubscript{STJ}</td>
<td>strengthening</td>
</tr>
<tr>
<td>ψ\textsubscript{HC}</td>
<td>slight weakening</td>
</tr>
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CMIP5: CO$_2$ Response

<table>
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<tr>
<td>$\varphi_{HC}$</td>
<td>poleward</td>
</tr>
<tr>
<td>$\varphi(u'v')$</td>
<td>poleward</td>
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</tbody>
</table>

HC edge:
- latitude of max eddy momentum flux $\varphi(u'v')$

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Poleward Shift [°]

Years

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**CMIP5: CO₂ Response**

**HC edge:**
- latitude of max eddy momentum flux \( \phi(u'v') \)

**STJ strength:**
- max meridional temperature gradient \( \partial T / \partial y \)

<table>
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<tr>
<td>( \phi HC )</td>
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<td>( \partial T / \partial y )</td>
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Menzel et al. 2019
CMIP5: CO$_2$ Response
CMIP5: Interannual

HC:
- Expands (0.9°)
- Weakens (0.5x10^{10} \text{ kg s}^{-1})

EDJ:
- Shifts poleward (2°)
- Strengthens (0.8 m s^{-1})

STJ
- Shifts poleward (0.3°)
- Weakens (0.9 m s^{-1})

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CMIP5: CO₂ Response

HC:
- Expands (1.7°)
- Weakens (0.4x10¹⁰ kg s⁻¹)

EDJ:
- Shifts poleward (2.9°)
- Strengthens (1.6 m s⁻¹)

STJ
- Shifts poleward (0.4°)
- Strengthens (4.4 m s⁻¹)
## CMIP5: Interannual Correlations

### Southern Hemisphere

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<td>$\phi_{EDJ}$</td>
<td>-0.02 (0.24)</td>
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<td>-0.09 (0.08)</td>
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<tr>
<td>$\phi_{STJ}$</td>
<td>0.01 (0.16)</td>
<td>-0.39 (0.35)</td>
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<tr>
<td>maxEDJ</td>
<td>0.08 (0.15)</td>
<td>0.04 (0.29)</td>
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CMIP5: CO$_2$ Response

Response to 4xCO$_2$

- $\Delta \phi_{STJ}$
  - NH: $R = 0.41$
  - SH: $R = 0.5$

- $\Delta \phi_{HC}$
  - NH: $R = 0.22$
  - SH: $R = 0.16$

- $\Delta_{maxSTJ}$
  - NH: $R = 0.04$
  - SH: $R = 0.69$

- $\Delta_{maxHC}$
CMIP5: CO$_2$ Response

- Upper graph: CO$_2$ concentration in ppm, constant at approximately 400 ppm from 0 to 150 years.
- Lower graph: Change in mean sea surface temperature ($\Delta\langle T_s \rangle$) in °C, showing a gradual increase from 2 to 8 °C over the same time period.
Dry Dynamical Core

GFLD Spectral Core

Equilibrium Temperature (Held and Suarez 1994)

\[ T_{eq} = \max \left\{ 200, \left[ 315 - \delta_y (\sin \phi)^2 + T' - \delta_z \log \left( \frac{p}{p_0} \right) (\cos \phi)^2 \right] \left( \frac{p}{p_0} \right)^\kappa \right\} \]
Dry Dynamical Core

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Tropical Warming (Sun et al. 2013)

\[ T' = \delta_y \left\{ [A + (\sin \phi)^{1.25} - (\sin \phi)^2] \left[ 0.5 \left( 1 - \tanh \left( \frac{\phi - \phi_0}{\delta \phi} \right) \right) \right] \right\} \]

<table>
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<th>Narrow</th>
<th>Broad</th>
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<td>( \phi_0 = 10^\circ )</td>
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Warming Width

Narrow Forcing
HC: Contracts (3.1°), strengthens (3.9(10^{10}) kg s^{-1})
EDJ: Shifts equatorward (4.8°)
STJ: Strengthens (4.5 m s^{-1})
Warming Width

Narrow Forcing
HC: Contracts (3.1°), strengthens (3.9 \times 10^{10} \text{ kg s}^{-1})
EDJ: Shifts equatorward (4.8°)
STJ: Strengthens (4.5 \text{ m s}^{-1})

Broad Forcing
HC: Slight expansion (1.1°)
EDJ: Shifts poleward (1.7°)
STJ: Strengthens (3.9 \text{ m s}^{-1})
Warming Width

Narrow Forcing
HC: Contracts, strengthens
EDJ: Shifts equatorward
STJ: Strengthens

Broad Forcing
HC: Slight expansion
EDJ: Shifts poleward
STJ: Strengthens
Key Takeaways

1. **CMIP5 analysis shows the STJ latitude does not co-vary interannually with the Hadley Cell HC edge but the STJ strength does moderately**

<table>
<thead>
<tr>
<th></th>
<th>Southern Hemisphere</th>
<th>Northern Hemisphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>eHC maxSTJ</td>
<td>ANN -0.19, DJF -0.34, MAM -0.14, JJA -0.25*, SON -0.1</td>
<td>ANN -0.39*, DJF -0.3*, MAM -0.52*, JJA -0.29*, SON -0.15</td>
</tr>
</tbody>
</table>

2. **The interannual relationship between HC edge and STJ strength is the opposite sign as the response to increased atmospheric CO₂**

3. **The differences in the HC-STJ relationship are related to the differing sensitivities of the HC and STJ to shifts in eddy momentum fluxes**

Future Work

What are the underlying physical processes that dictate the behavior of the STJ and HC?
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What are the underlying physical processes that dictate the behavior of the STJ and HC?

MODEL: Aquaplanet Simulations
- Warming of various widths
- Polar cooling
- Disable eddy parameterizations

<table>
<thead>
<tr>
<th>Run</th>
<th>Δ&lt;T_s&gt;</th>
<th>Δφ_T</th>
<th>Eddy permitting</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5K</td>
<td>5°-45°</td>
<td>yes</td>
</tr>
<tr>
<td>2</td>
<td>3K</td>
<td>5°-45°</td>
<td>yes</td>
</tr>
<tr>
<td>3</td>
<td>1.5K</td>
<td>5°-45°</td>
<td>no</td>
</tr>
<tr>
<td>4</td>
<td>-1.5K</td>
<td>60°-90°</td>
<td>yes</td>
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\[ \phi = 10° \]

\[ \phi = 30° \]
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ANALYSIS:
Momentum Budget
- Role of eddy momentum fluxes
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Questions?