Disconnect Between Hadley Cell and Subtropical Jet Variability and Response to Increased CO_2

Molly Menzel[1], Darryn Waugh[1,2], Kevin Grise[3]

October 22, 2019

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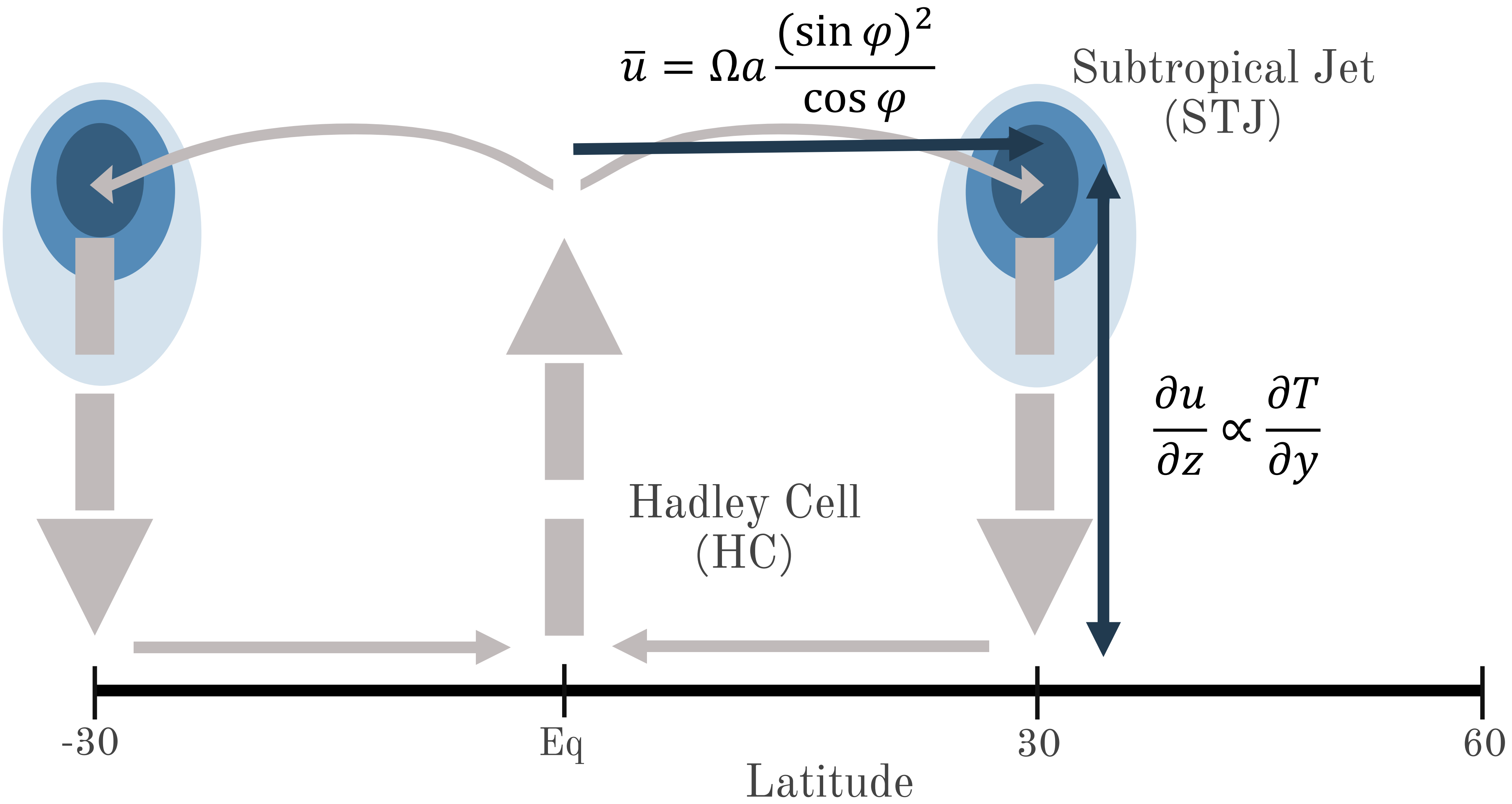
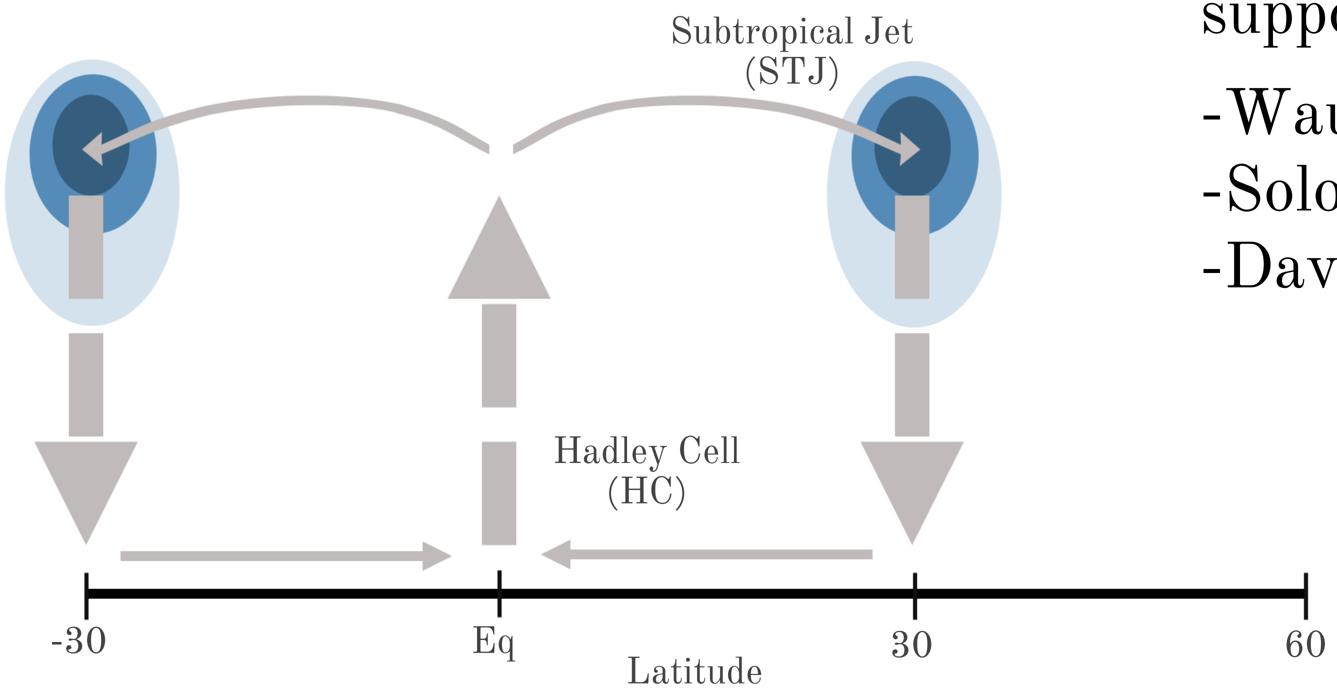
Subtropical Jet and Hadley Cell Relationship



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

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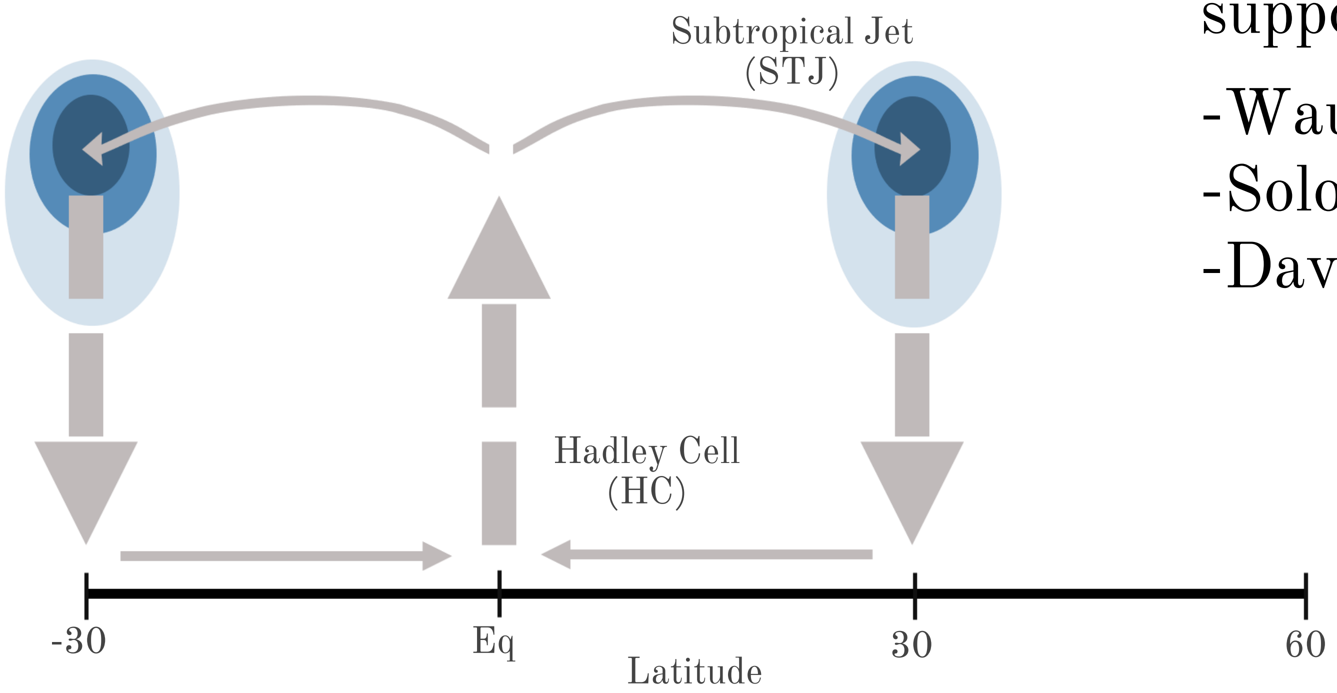

… the reanalyses and models do not support this.

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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 4xCO_2 forcing?*

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

Metrics

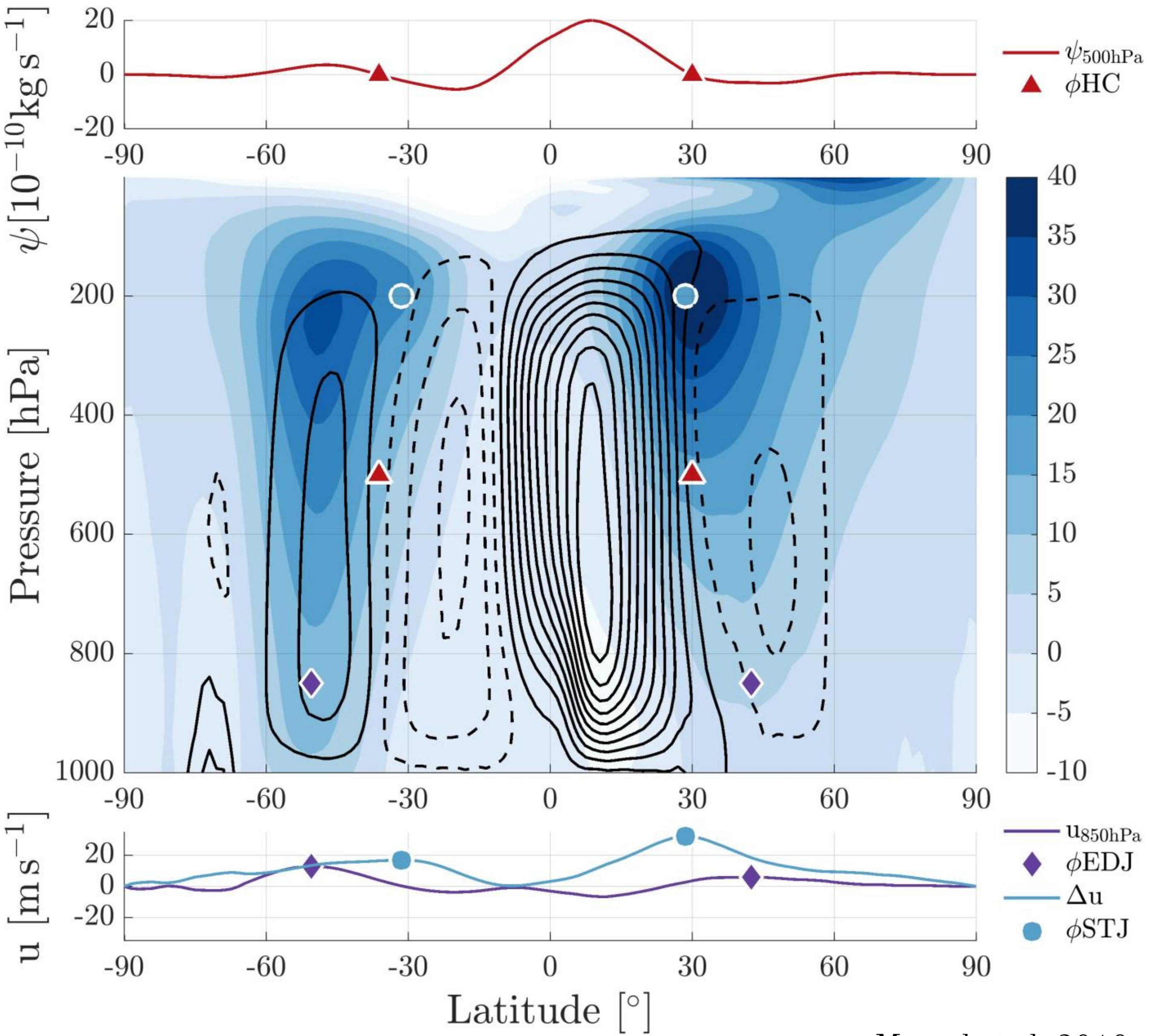
Metrics

Hadley Cell

"PSI500"

▲ $\varphi HC = \varphi(\psi_{500\,hPa} = 0)$

$\psi HC = max(\psi_{500\,hPa})$



Menzel et al. 2019

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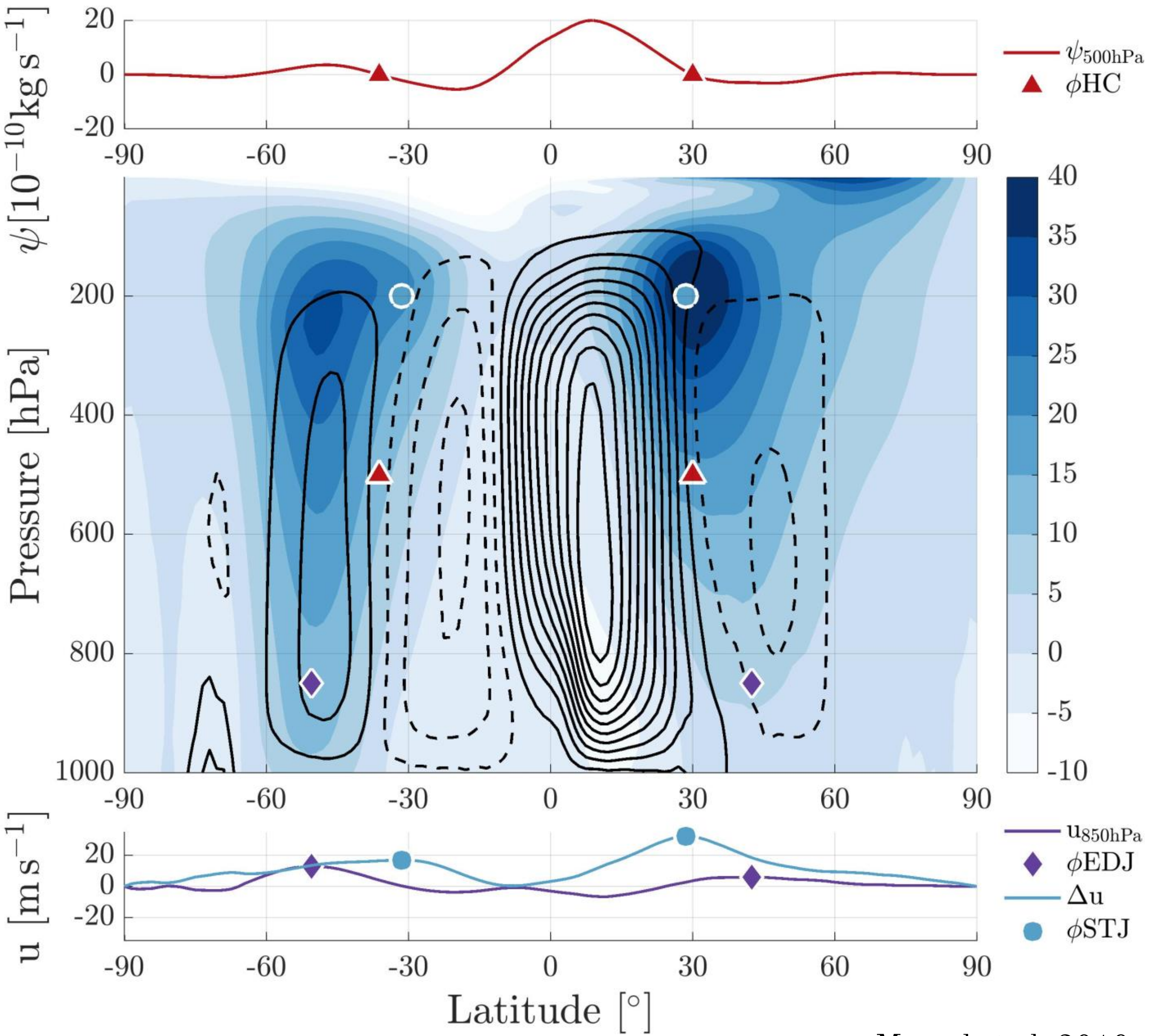
Eddy-Driven Jet (EDJ)

◆ $\varphi EDJ = \varphi(\max(u_{850\,hPa}))$



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Eddy-Driven Jet (EDJ)

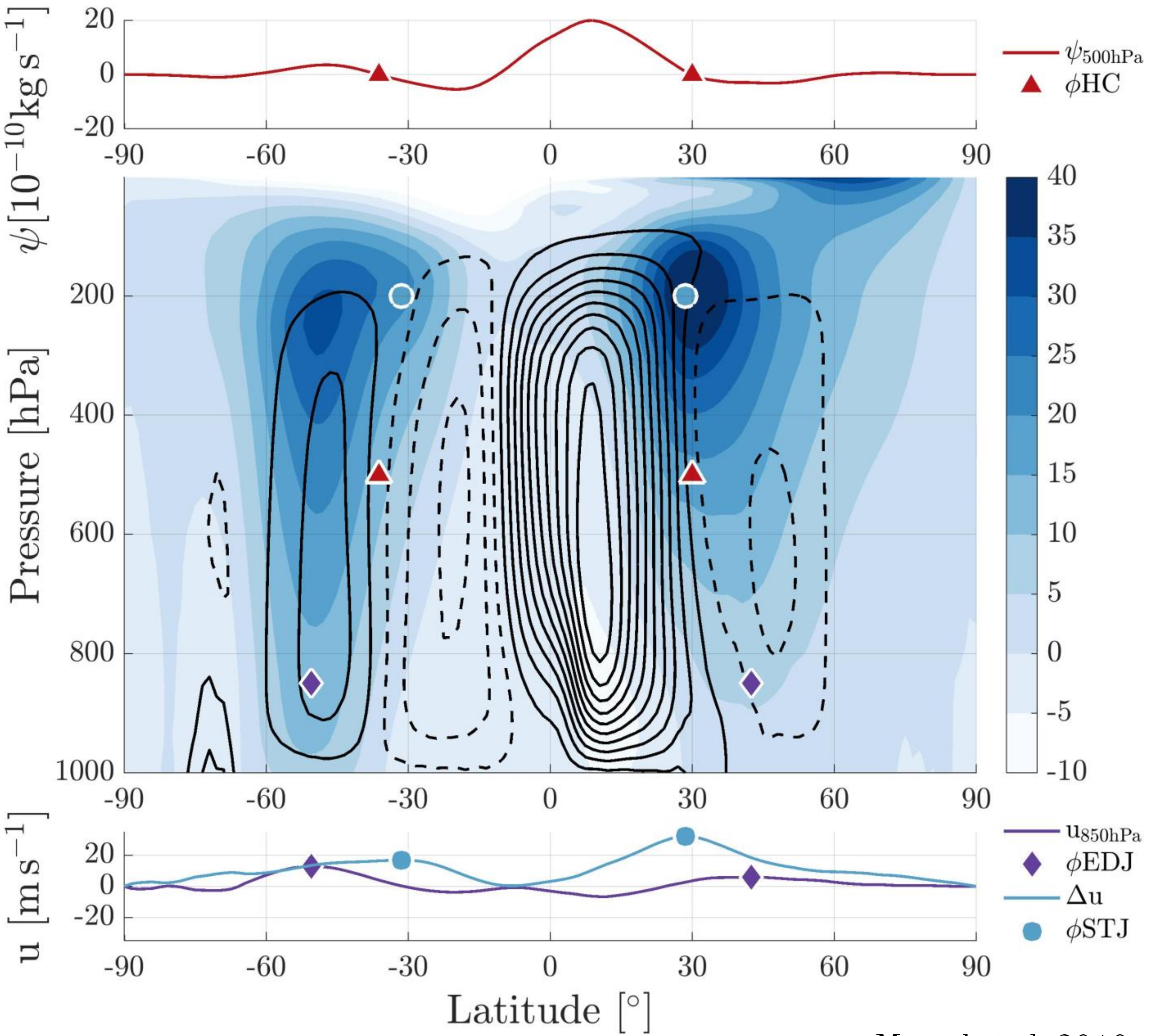
◆ $\varphi EDJ = \varphi(\max(u_{850\,hPa}))$

Subtropical Jet (STJ)

● $\varphi STJ = \varphi(max(\Delta u))$

$uSTJ = \Delta u(\varphi STJ)$

$\Delta u = u_{100-400\,hPa} - u_{850\,hPa}$



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CMIP5 Analysis

CMIP5 Data

Coupled Model Intercomparison Project
(Phase 5)

Output from coupled simulations

piControl

Control with
pre-industrial
levels of CO_2

CMIP5 Data

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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

ACCESS1-0	GISS-E2-R
bcc-csm1-1-m	HadGEM2-ES
bcc-csm1-1	Inmcm4
CanESM2	IPSL-CM5A-LR
CCSM4	IPSL-CM5B-LR
CNRM-CM5	MIROC5
CSIRO-Mk3-6-0	MIROC-ESM
FGOALS-s2	MPI-ESM-LR
GFDL-CM3	MPI-ESM-P
GFDL-ESM2G	MRI-CGCM3
GFDL-ESM2M	NorESM1-M
GISS-E2-H	

CMIP5: Interannual

HC
– Expands, weakens

EDJ
– Shifts poleward, strengthens

STJ
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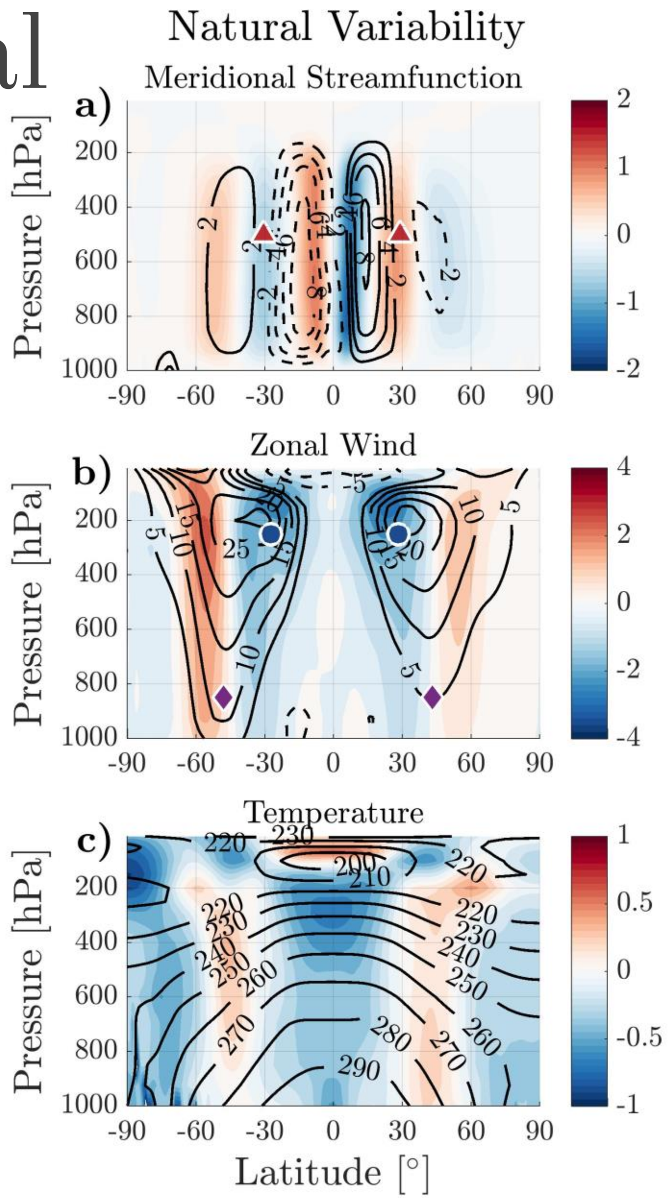

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Expanded HC
- contracted HC

$$\sum_t u(\phi HC > 2\sigma)$$

$$-\sum_t u(\phi HC < 2\sigma)$$

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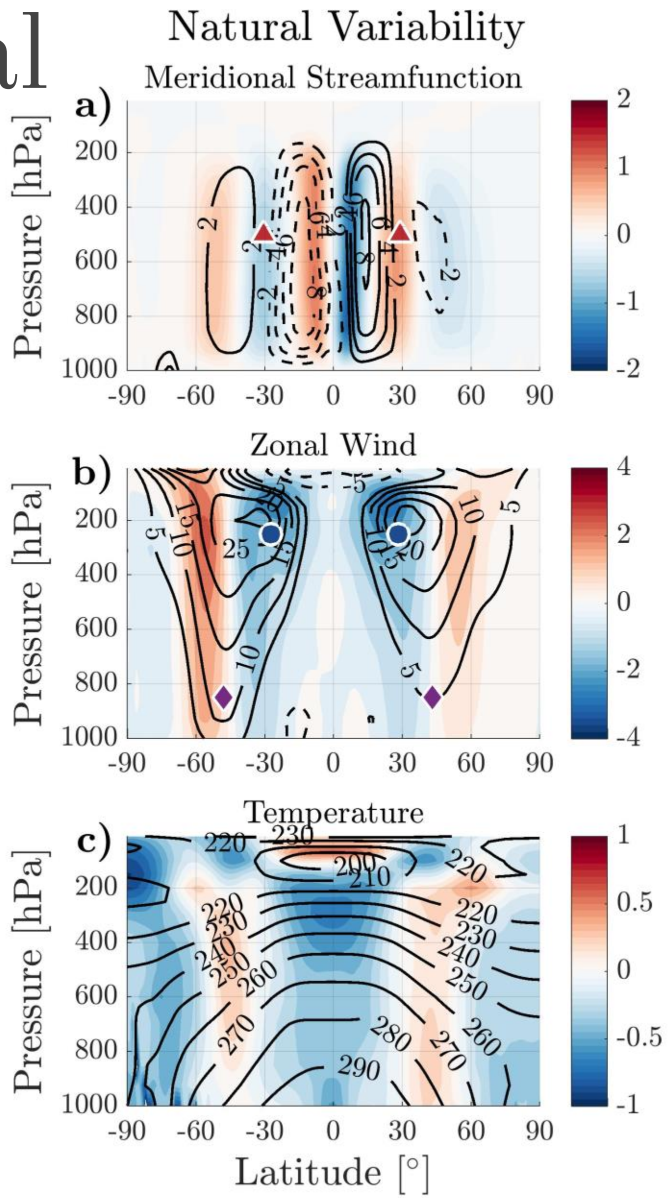
narrow tropical cooling



Menzel et al. 2019

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CMIP5: Interannual

	Southern Hemisphere					Northern Hemisphere				
	ANN	DJF	MAM	JJA	SON	ANN	DJF	MAM	JJA	SON
ϕHC ϕSTJ	**0.07** (0.23)	**-0.1** (0.3)	**0.1** (0.22)	**0.12** (0.15)	**-0.03** (0.22)	**0.15** (0.18)	**0.02** (0.12)	**0.29*** (0.16)	**0.2** (0.17)	**-0.08** (0.09)
ϕHC maxSTJ	**-0.19** (0.16)	**-0.34** (0.26)	**-0.14** (0.16)	**-0.25*** (0.13)	**-0.1** (0.17)	**-0.39*** (0.14)	**-0.3*** (0.13)	**-0.52*** (0.13)	**-0.29*** (0.18)	**-0.15** (0.15)

Menzel et al. 2019

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	Natural Variability
HC Location STJ Strength	−

More poleward HC, weaker STJ

CMIP5: Response

HC
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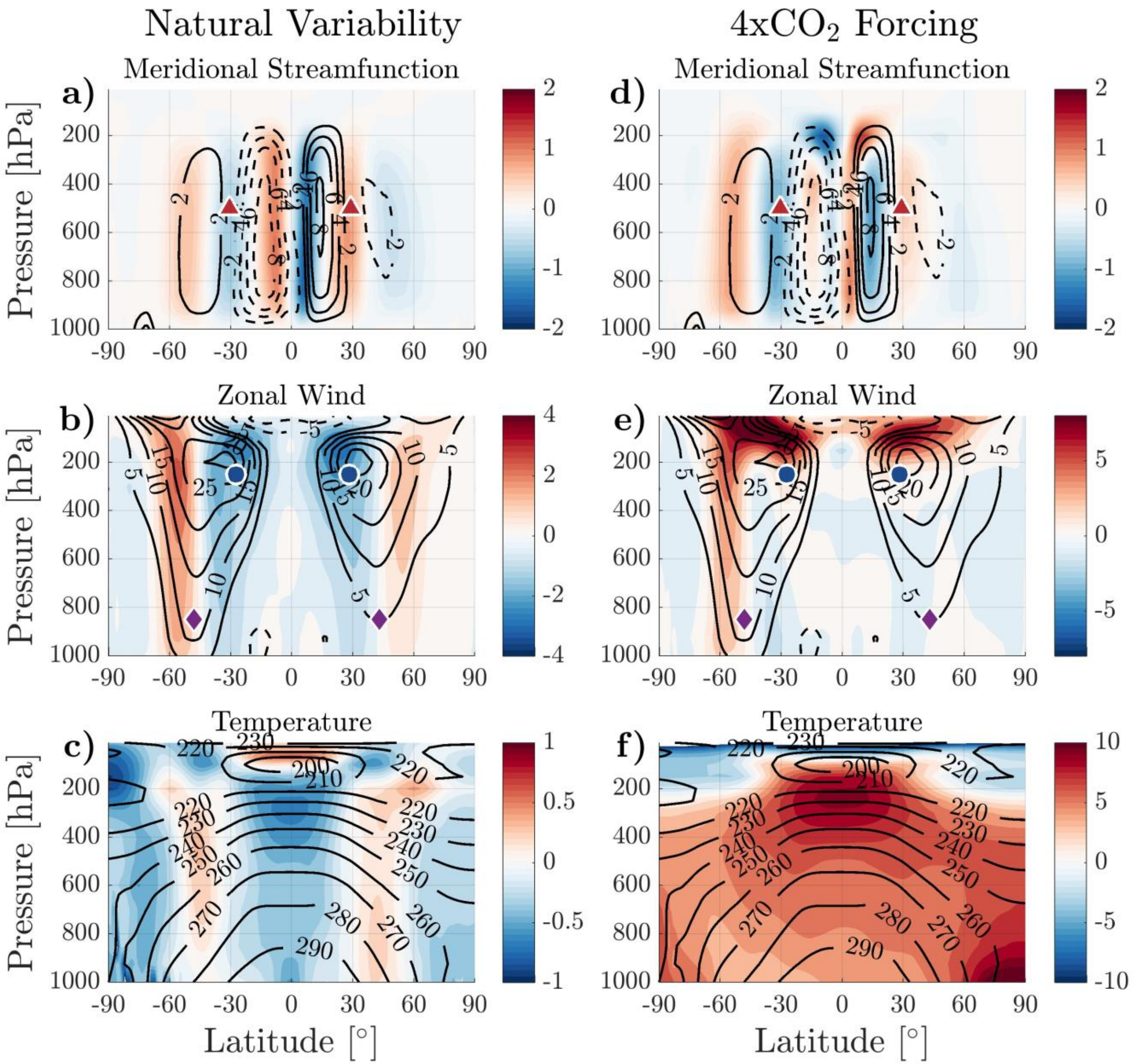

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CMIP5: Response

HC
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EDJ
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STJ
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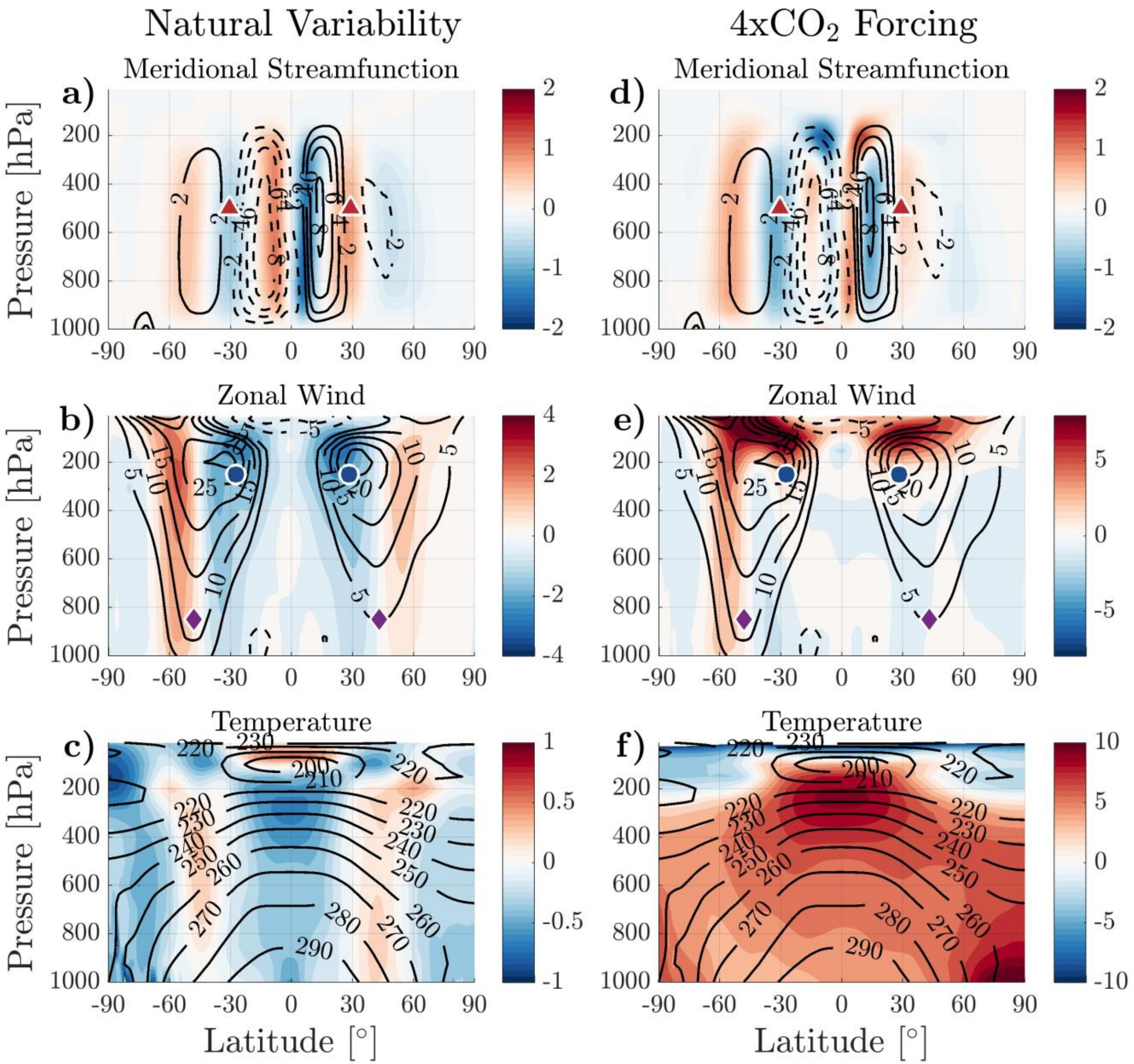
broad warming



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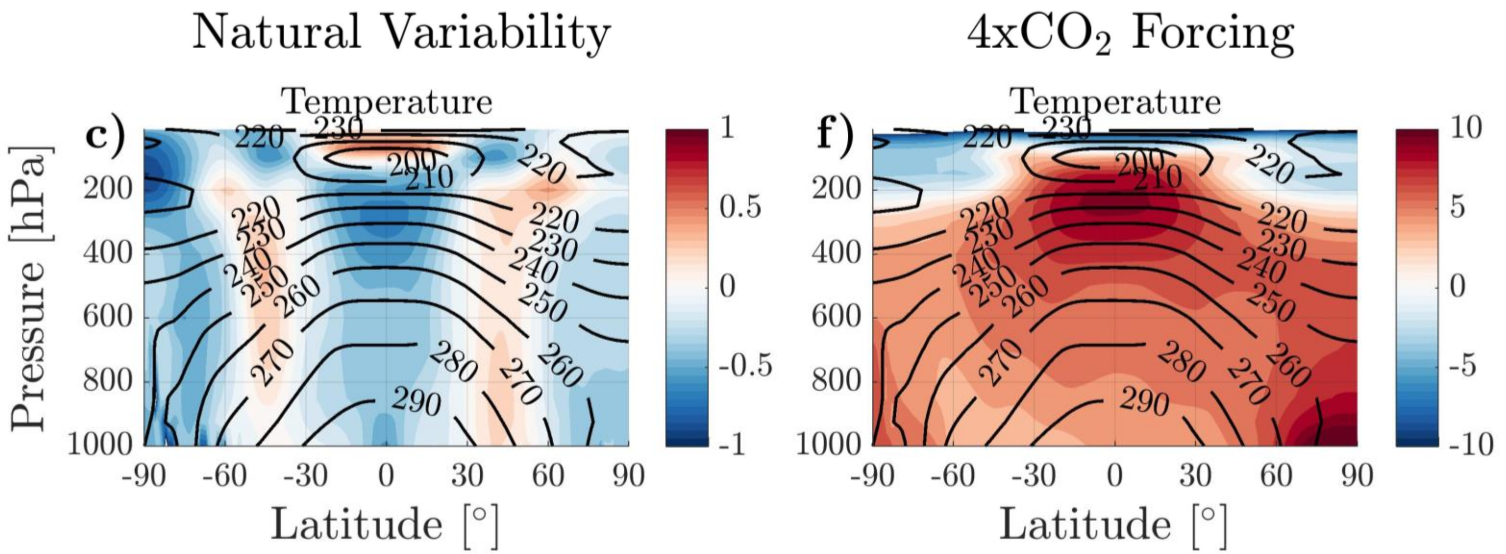
CMIP5: CO_2 Response

	Natural Variability	Response to 4xCO2
HC Location STJ Strength	−	+
	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



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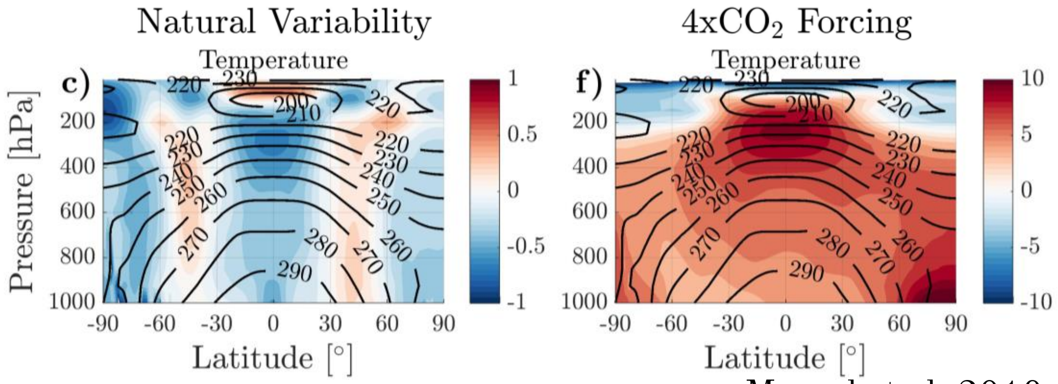

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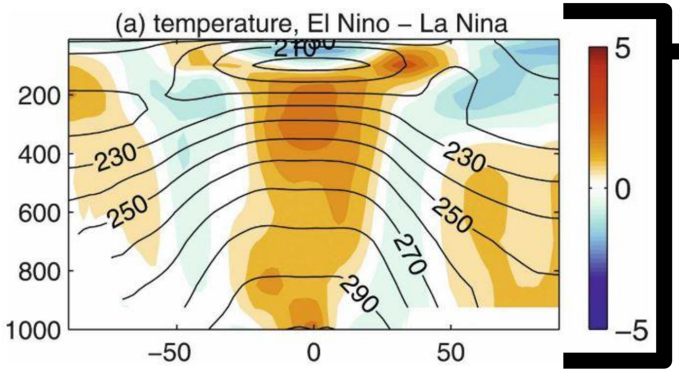
Narrow tropical warming (ENSO)



Lu et al. 2008

→ more narrow HC

Warming Width

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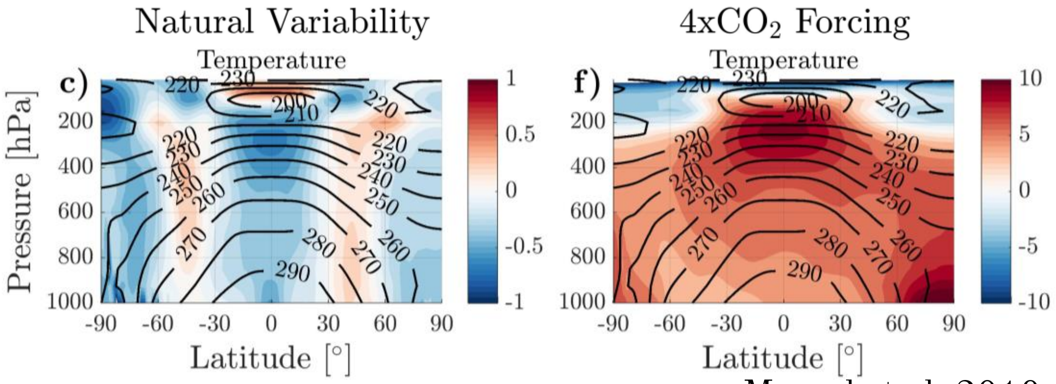
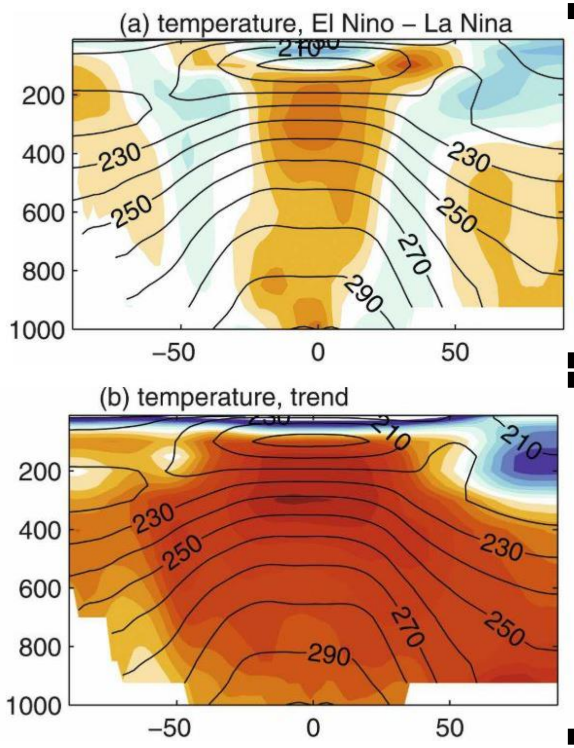


Menzel et al. 2019

Narrow tropical warming (ENSO)

Broad warming (global forcing)



Lu et al. 2008

→ more narrow HC

→ wider HC

Warming Width

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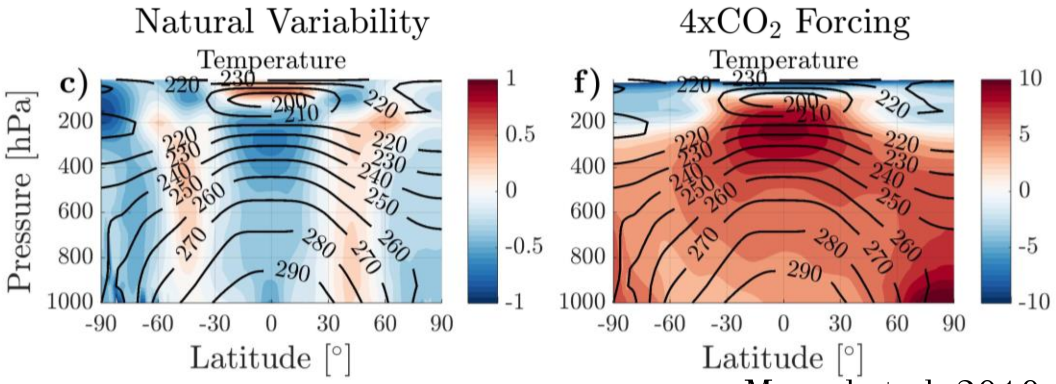

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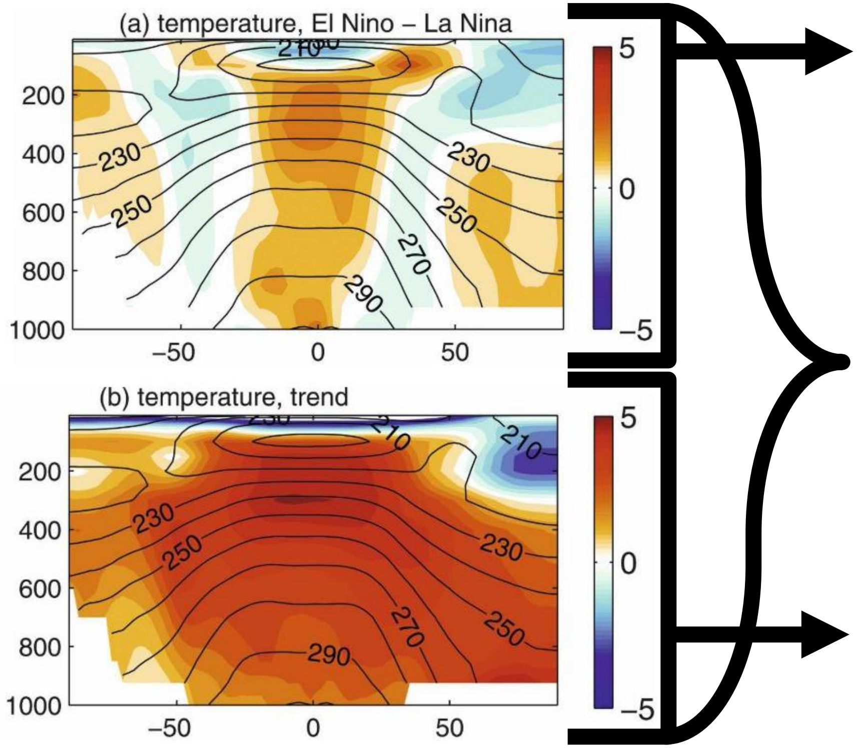


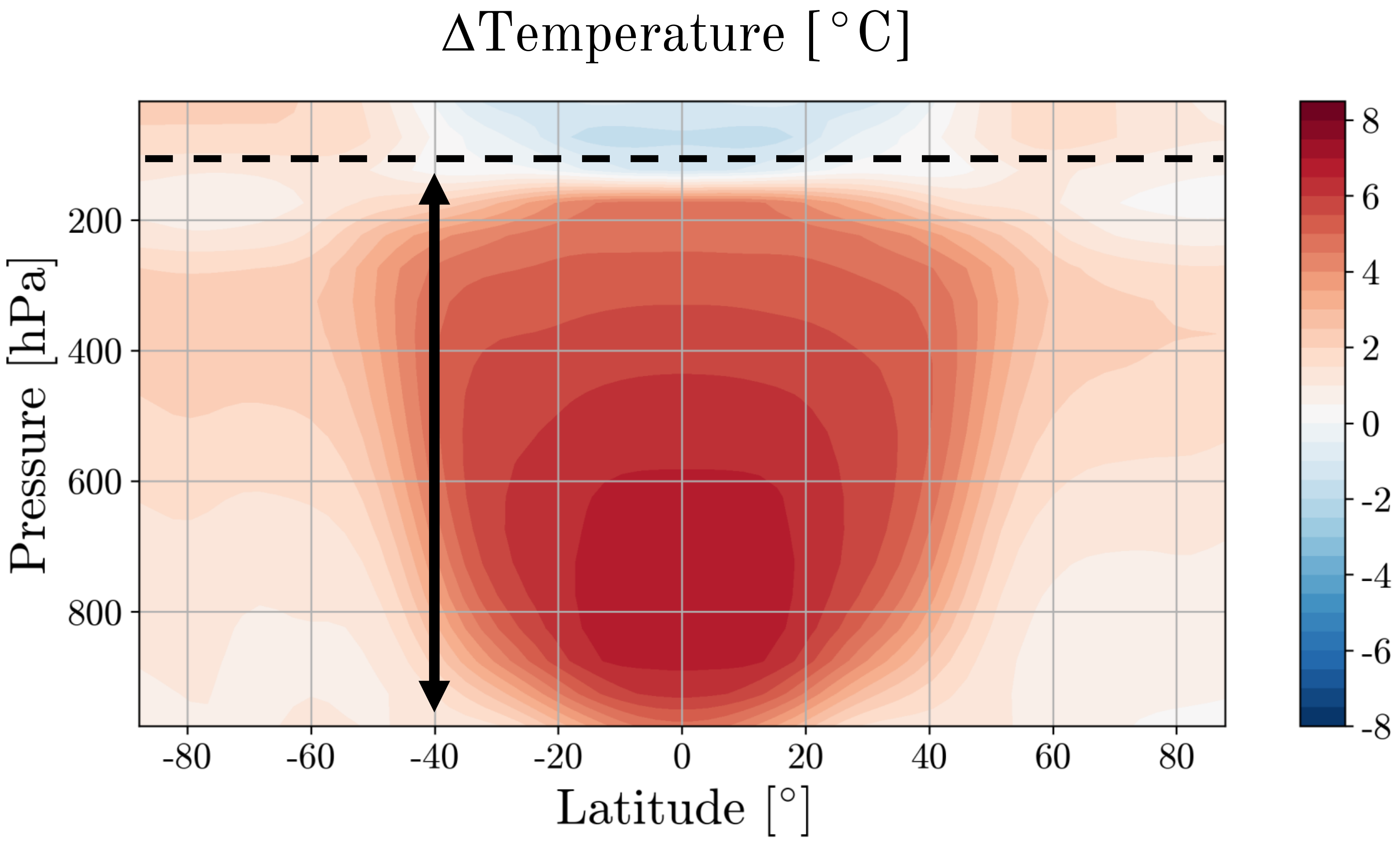
Lu et al. 2008

more narrow HC

stronger STJ

wider HC

Warming Metrics



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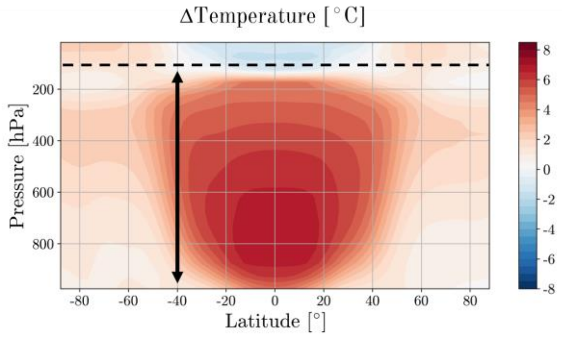
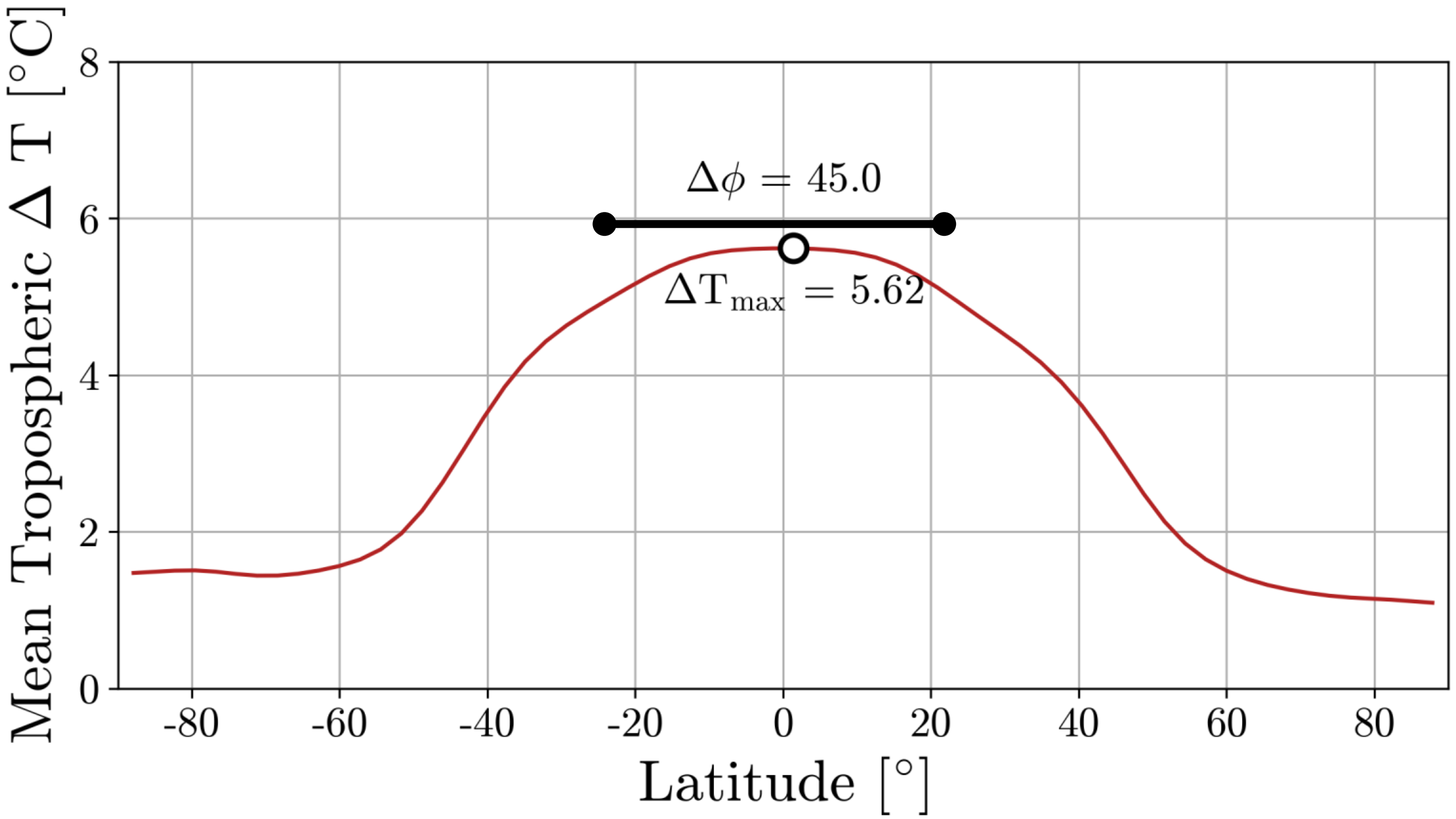


Warming Strength

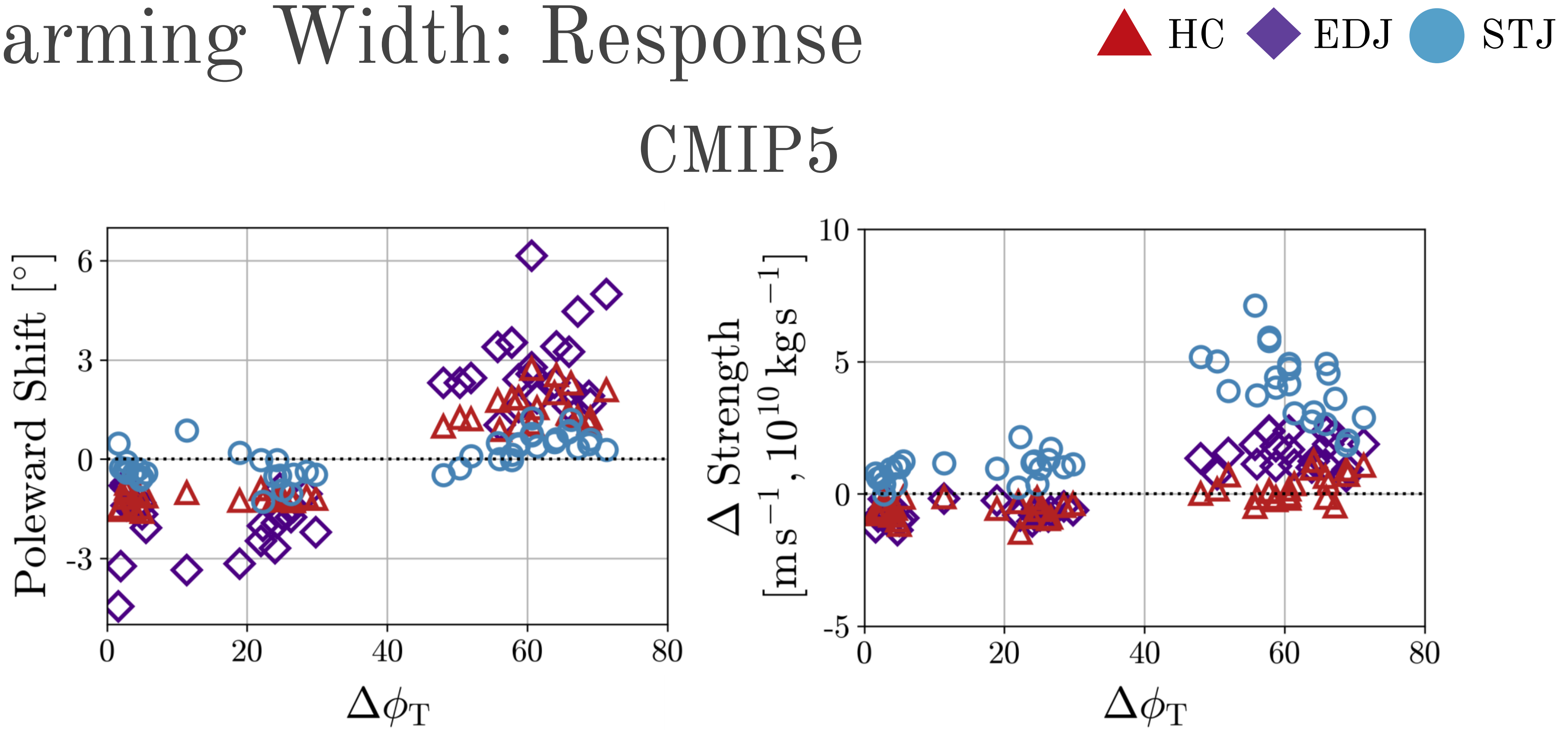
$\Delta T_{max} = max(\Delta T_{30S-30N})$

Warming Width

$\Delta \phi_T = \Delta \phi_{10\% \Delta T_{max}}$



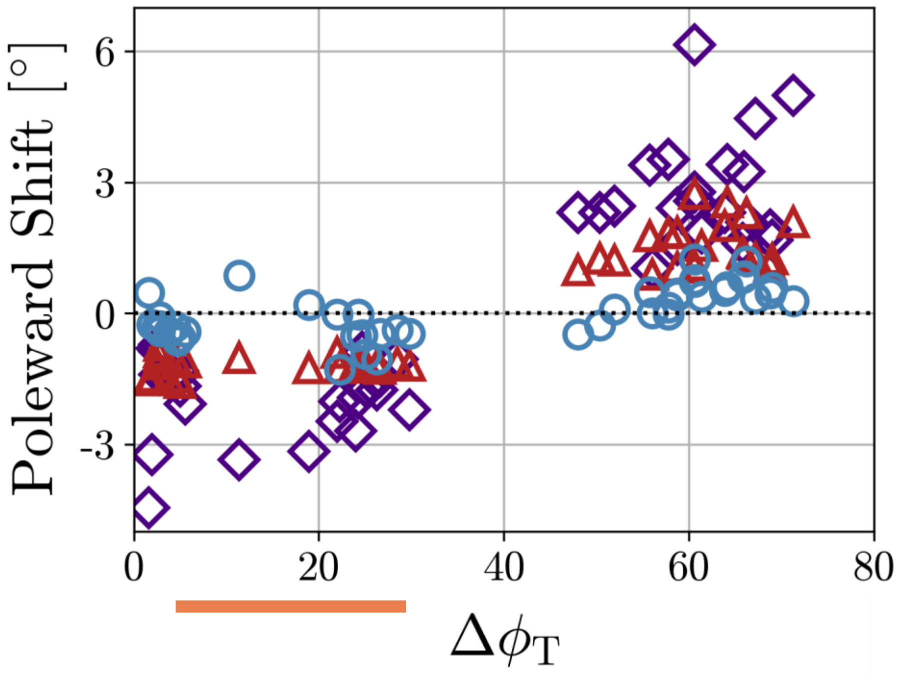
Warming Width: Response

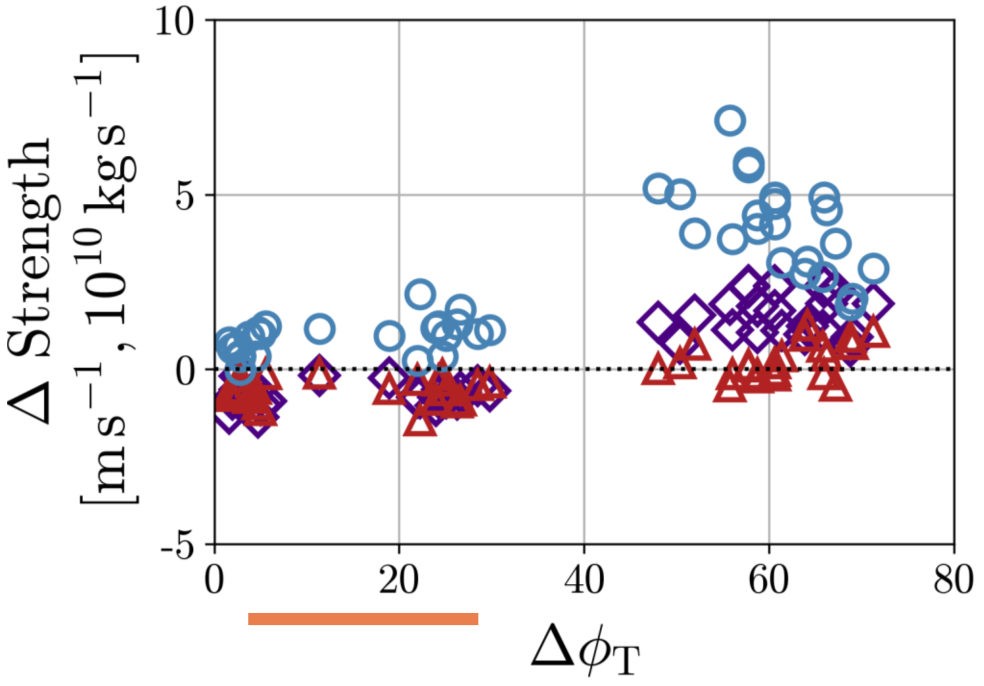


Warming Width: Response

HC EDJ STJ

CMIP5

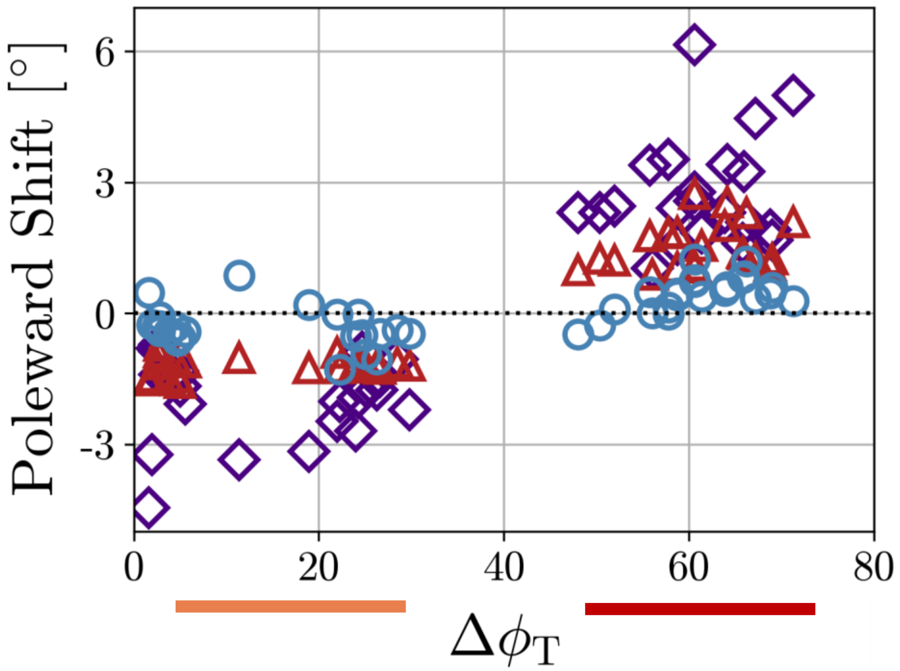


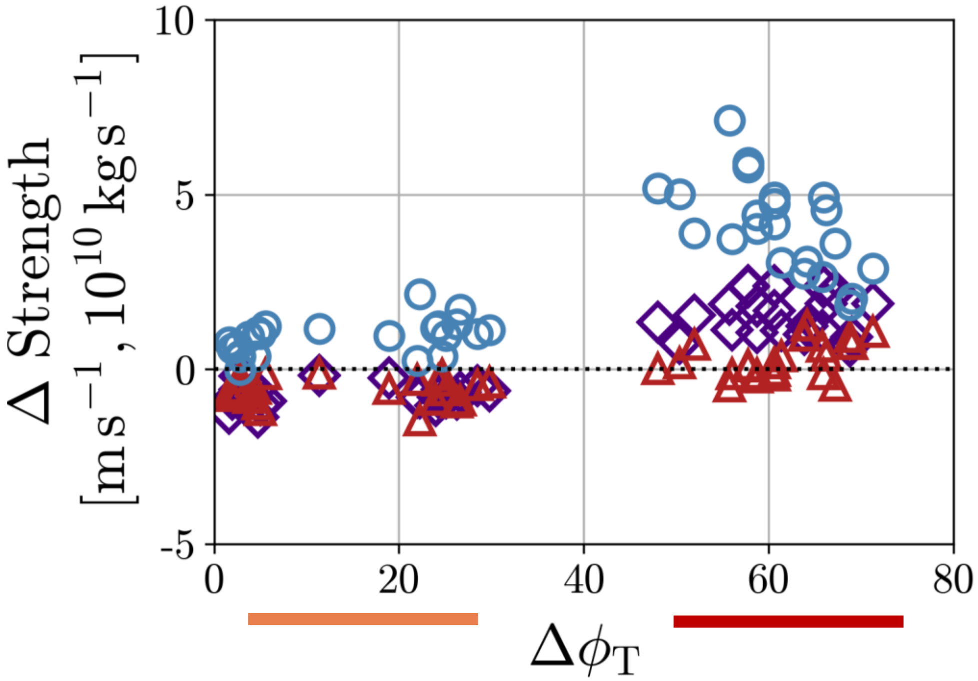


Narrow tropical warming:
HC contracts, STJ strengthens

Warming Width: Response

CMIP5





Narrow tropical warming:
HC contracts, STJ strengthens

Broad global warming:
HC expands, STJ strengthens

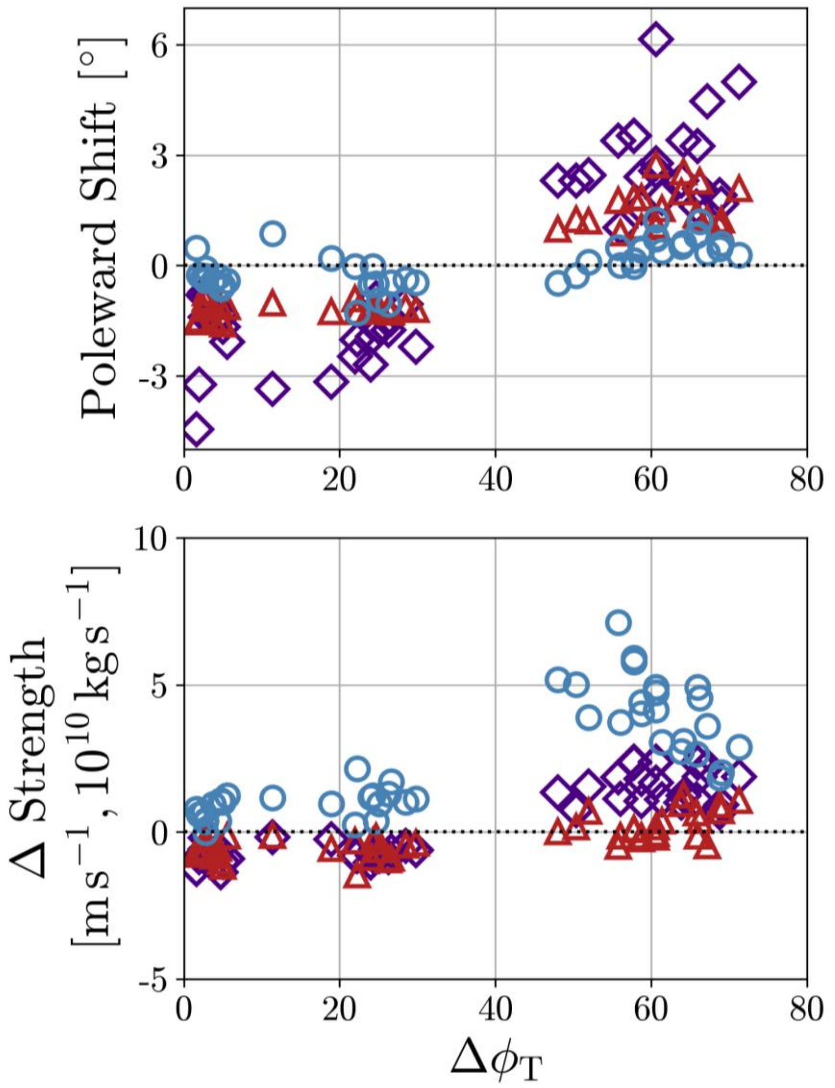
Warming Width: Response

How consistent is this response?

Comparing with idealized atmospheric models:

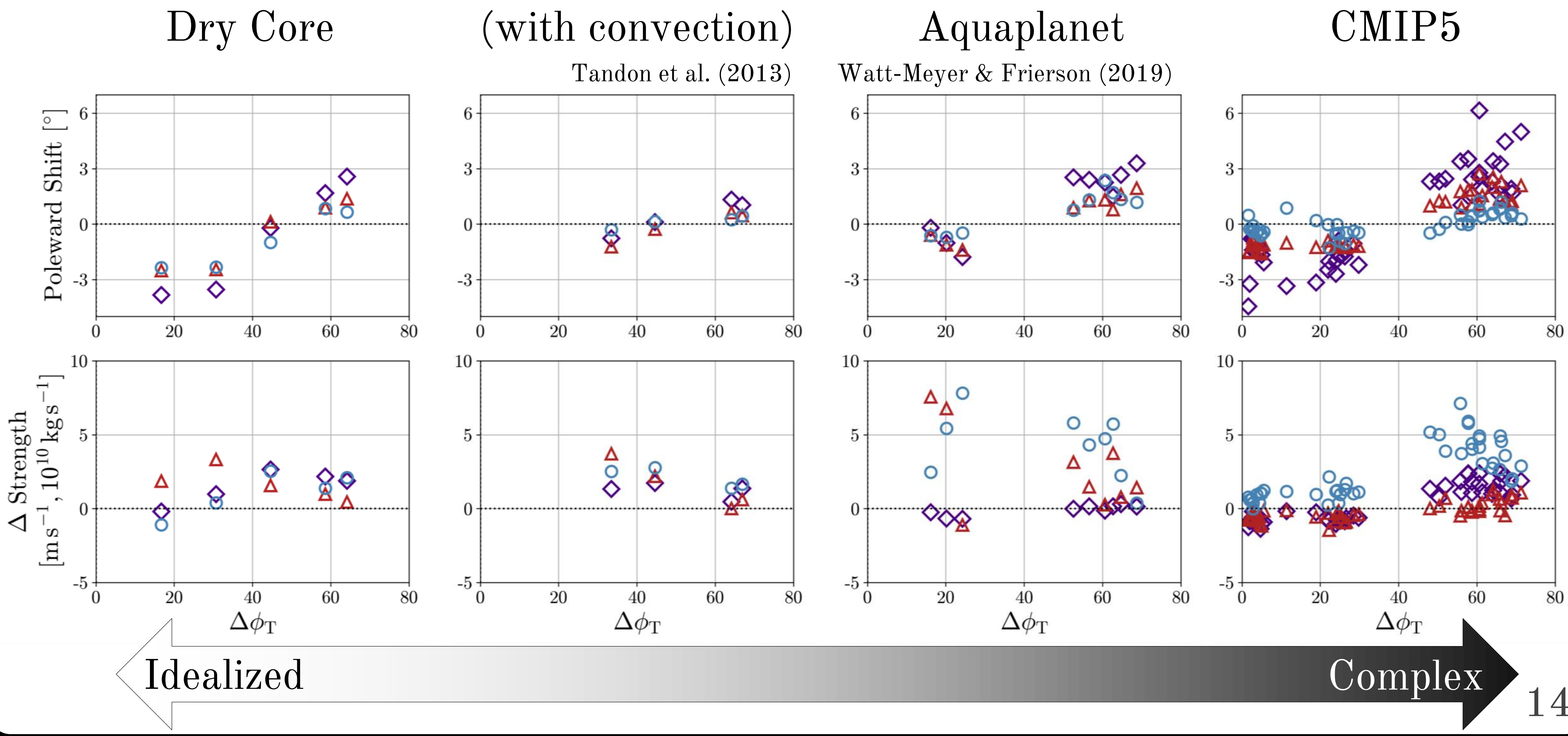
- GFDL dry dynamical core
  Temperature perturbation as in Sun et al. 2013
- GFDL dry core with convection parameter
  Data from Tandon et al. 2013
- Aquaplanet with specified SSTs
  Data from Watt-Meyer and Frierson 2019

CMIP5



Warming Width: Response

HC EDJ STJ



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

	Southern Hemisphere					Northern Hemisphere				
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	Response to $4xCO_2$	τ
φHC	Poleward shift	7
$uSTJ$	strengthening	40

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1. The interannual relationship between HC edge and STJ strength is the opposite sign as the response to increased atmospheric CO_2

	Response to 4xCO_2	τ
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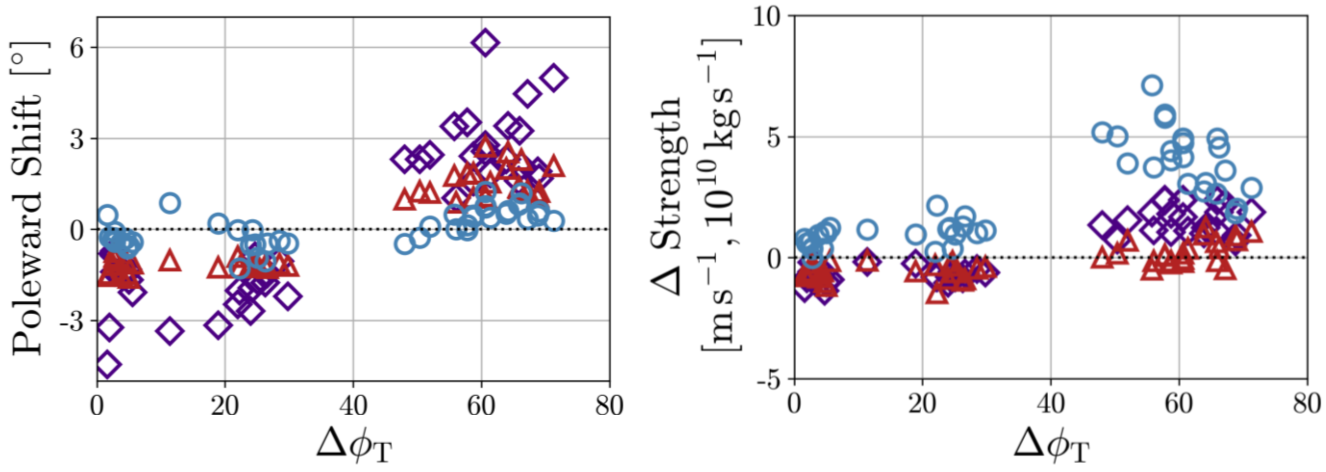
2. The STJ always strengthens given a warming while the HC's movement is dependent on the width of warming

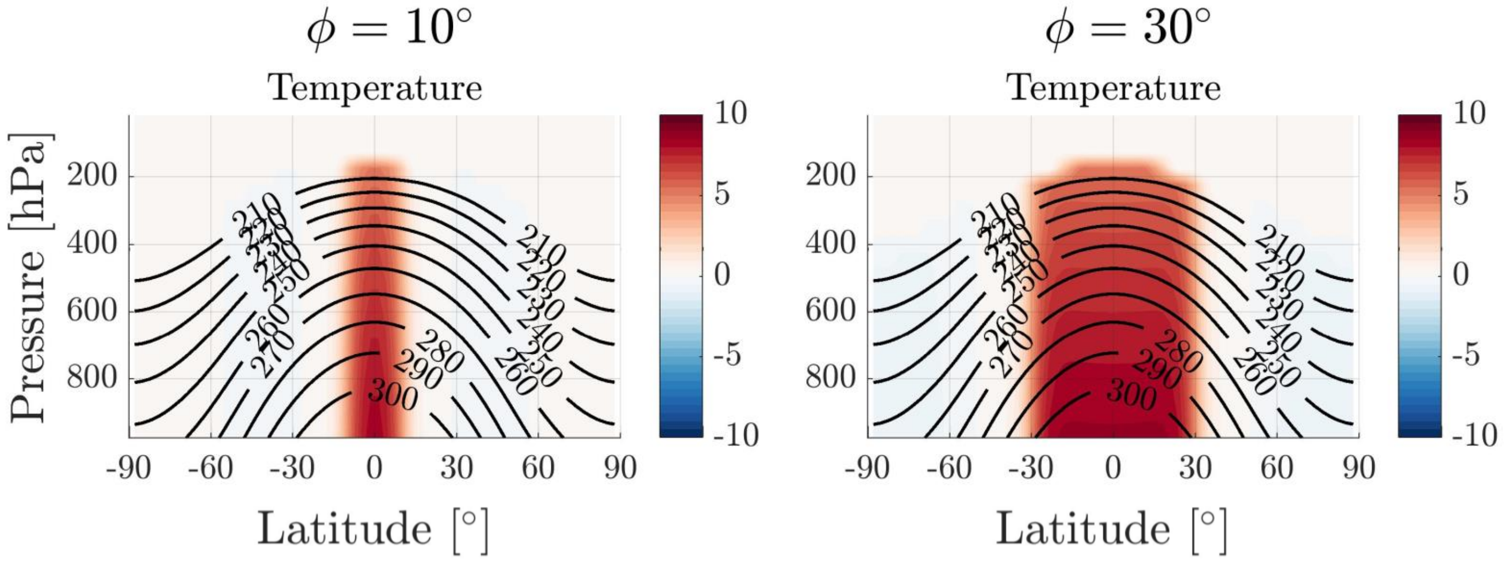


Future Work

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°)



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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°)

2. How are the STJ and HC sensitive to changes in midlatitude eddies?
   2nd Set of Runs: Zonally symmetric tropical warming
   (no waves)
   3rd Set of Runs: Polar cooling
   (60°-90°)

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

$$\frac{\partial u}{\partial t} = (f + \bar{\zeta})\bar{v} - \frac{1}{a\,cos^2\phi}\frac{\partial}{\partial\phi}\left(\overline{u'v'}cos^2\phi\right)$$

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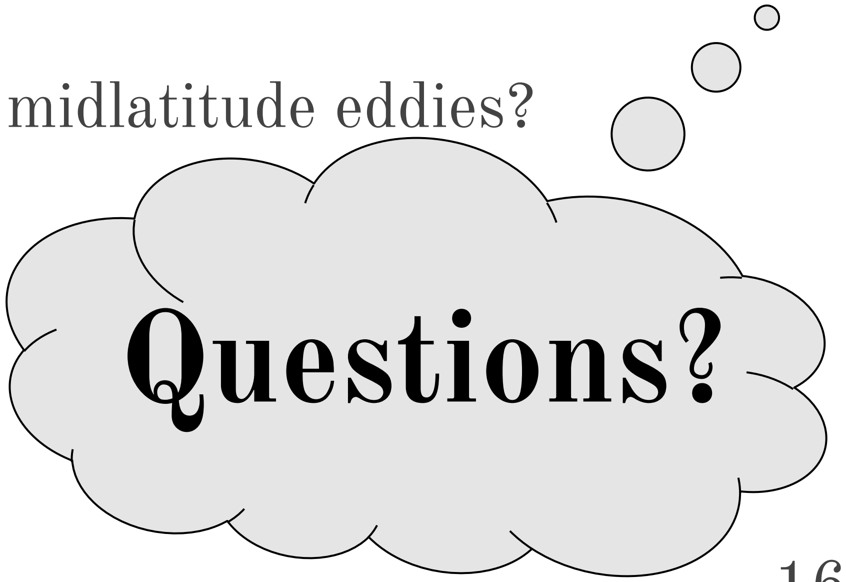

Extra Slides

CMIP5: Interannual Correlations

Southern Hemisphere

	ANN	DJF	MAM	JJA	SON
ϕHC / ϕSTJ	**0.07** (0.23)	**-0.1** (0.3)	**0.1** (0.22)	**0.12** (0.15)	**-0.03** (0.22)
ϕHC / maxSTJ	**-0.19** (0.16)	**-0.34** (0.26)	**-0.14** (0.16)	**-0.25*** (0.13)	**-0.1** (0.17)
maxHC / maxSTJ	**0.26** (0.19)	**0.06** (0.12)	**0.26*** (0.16)	**0.18** (0.15)	**0.22*** (0.15)
maxHC / ϕSTJ	**-0.07** (0.2)	**0.01** (0.08)	**-0.11** (0.15)	**-0.04** (0.18)	**-0.08** (0.21)
ϕSTJ / maxSTJ	**-0.35*** (0.15)	**-0.08** (0.17)	**-0.21** (0.15)	**-0.33*** (0.15)	**-0.27*** (0.16)
ϕHC / maxHC	**-0.4*** (0.11)	**0** (0.12)	**-0.31** (0.16)	**-0.23*** (0.12)	**-0.35*** (0.13)
ϕHC / ϕEDJ	**0.52*** (0.14)	**0.72*** (0.06)	**0.46*** (0.14)	**0.24** (0.17)	**0.4*** (0.21)

Northern Hemisphere

	ANN	DJF	MAM	JJA	SON
ϕHC / ϕSTJ	**0.15** (0.18)	**0.02** (0.12)	**0.29*** (0.16)	**0.2** (0.17)	**-0.08** (0.09)
ϕHC / maxSTJ	**-0.39*** (0.14)	**-0.3*** (0.13)	**-0.52*** (0.13)	**-0.29*** (0.18)	**-0.15** (0.15)
maxHC / maxSTJ	**0** (0.21)	**0.21** (0.18)	**0.39*** (0.19)	**-0.01** (0.06)	**0.12** (0.1)
maxHC / ϕSTJ	**0.03** (0.16)	**0.06** (0.12)	**-0.08** (0.19)	**-0.01** (0.11)	**-0.03** (0.12)
ϕSTJ / maxSTJ	**-0.37*** (0.15)	**-0.22** (0.17)	**-0.39*** (0.17)	**0.01** (0.18)	**-0.03** (0.14)
ϕHC / maxHC	**-0.33*** (0.18)	**-0.25** (0.15)	**-0.35*** (0.21)	**0.03** (0.09)	**-0.07** (0.14)
ϕHC / ϕEDJ	**0.52*** (0.1)	**0.47*** (0.11)	**0.48*** (0.11)	**0.4*** (0.11)	**0.45*** (0.08)

Colour scale: 1, 0.8, 0.6, 0.4, 0.2, 0, -0.2, -0.4, -0.6, -0.8, -1

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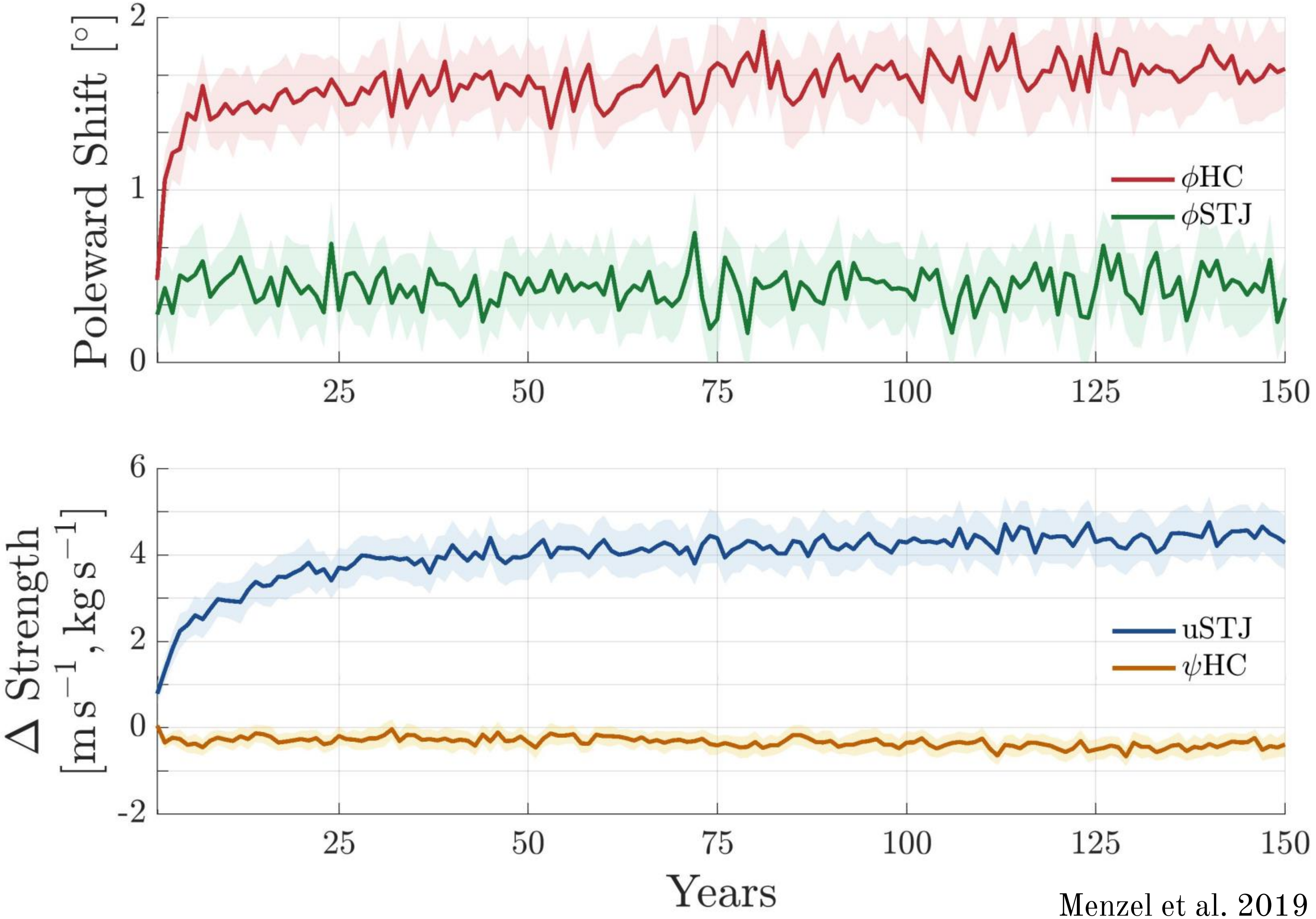
CMIP5: CO_2 Response



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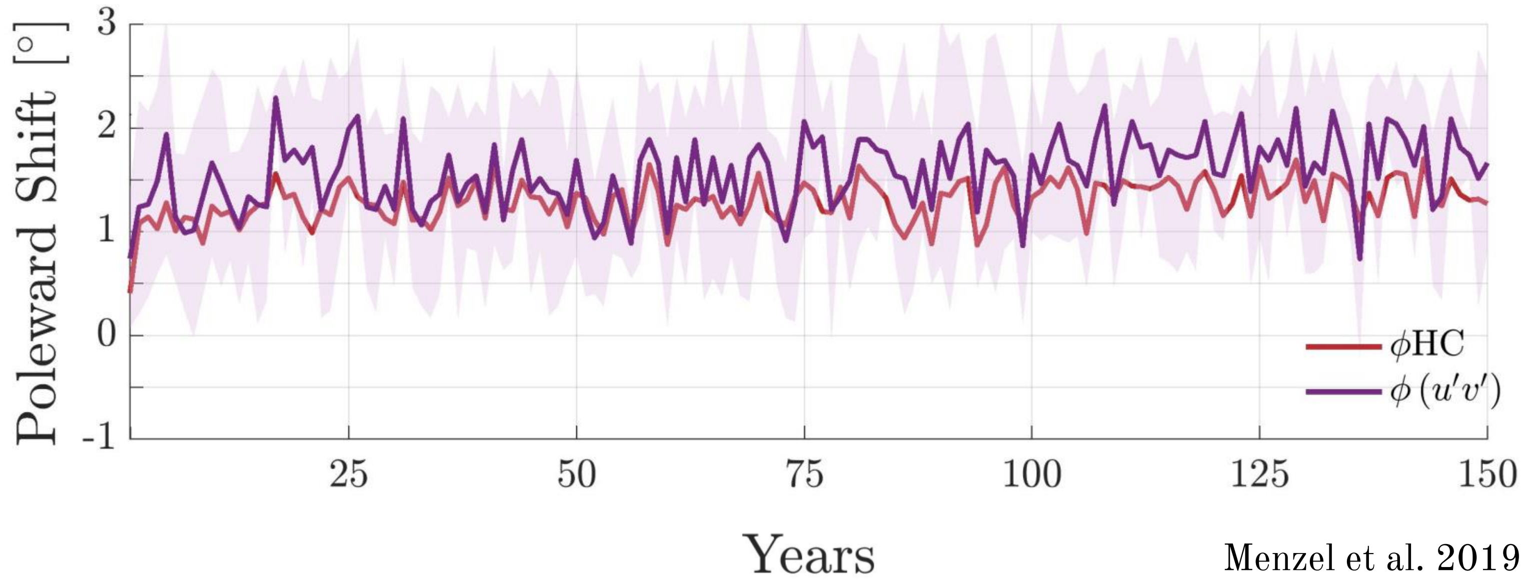
Time series of metrics' response to $4xCO_2$

	Shift/Change	τ
φHC	poleward	7
φSTJ	slight poleward	2
uSTJ	strengthening	40
ψHC	slight weakening	2

CMIP5: CO_2 Response



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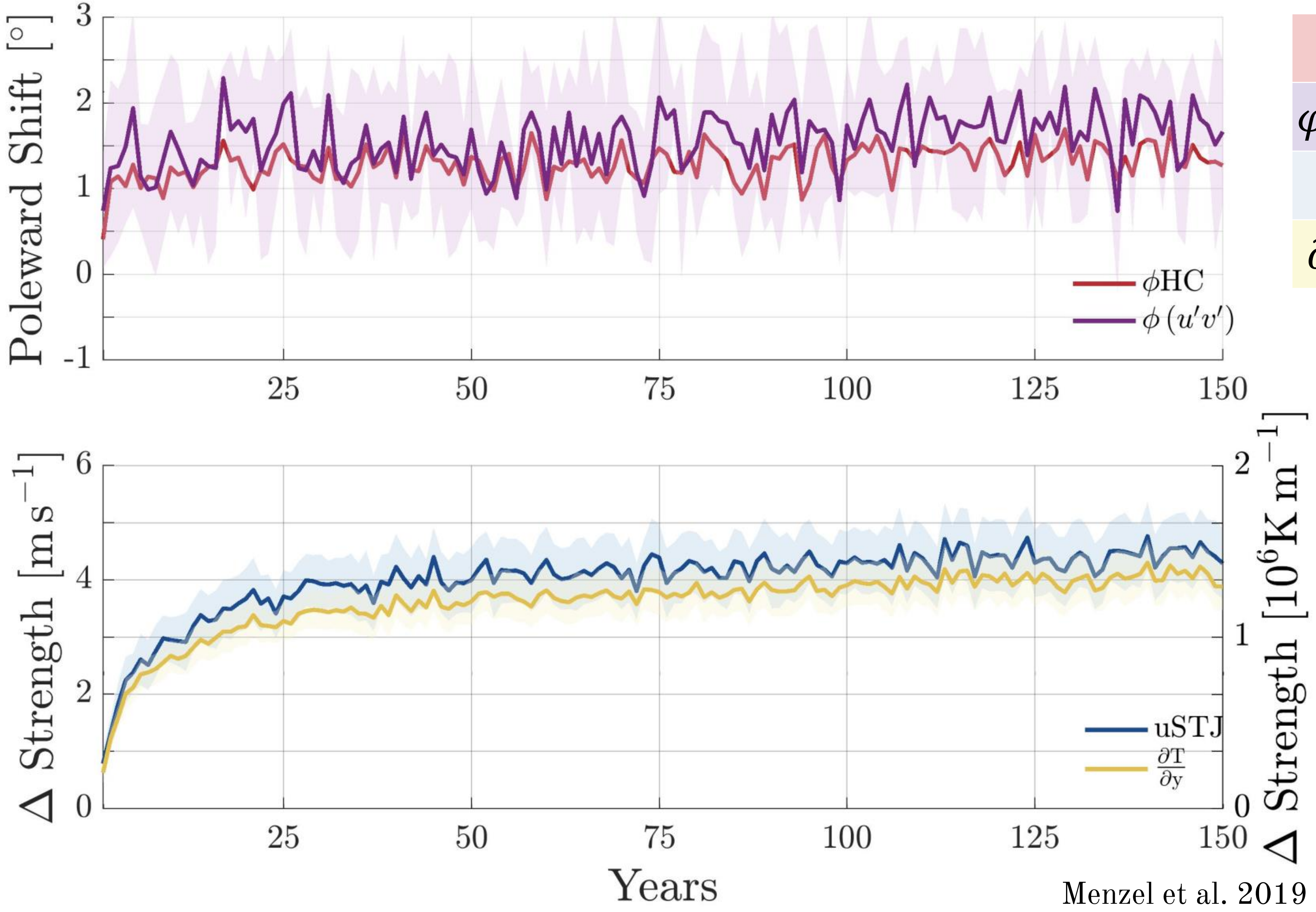
	Shift/Change	τ
φHC	poleward	7
$\varphi(u'v')$	poleward	5

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

CMIP5: CO_2 Response



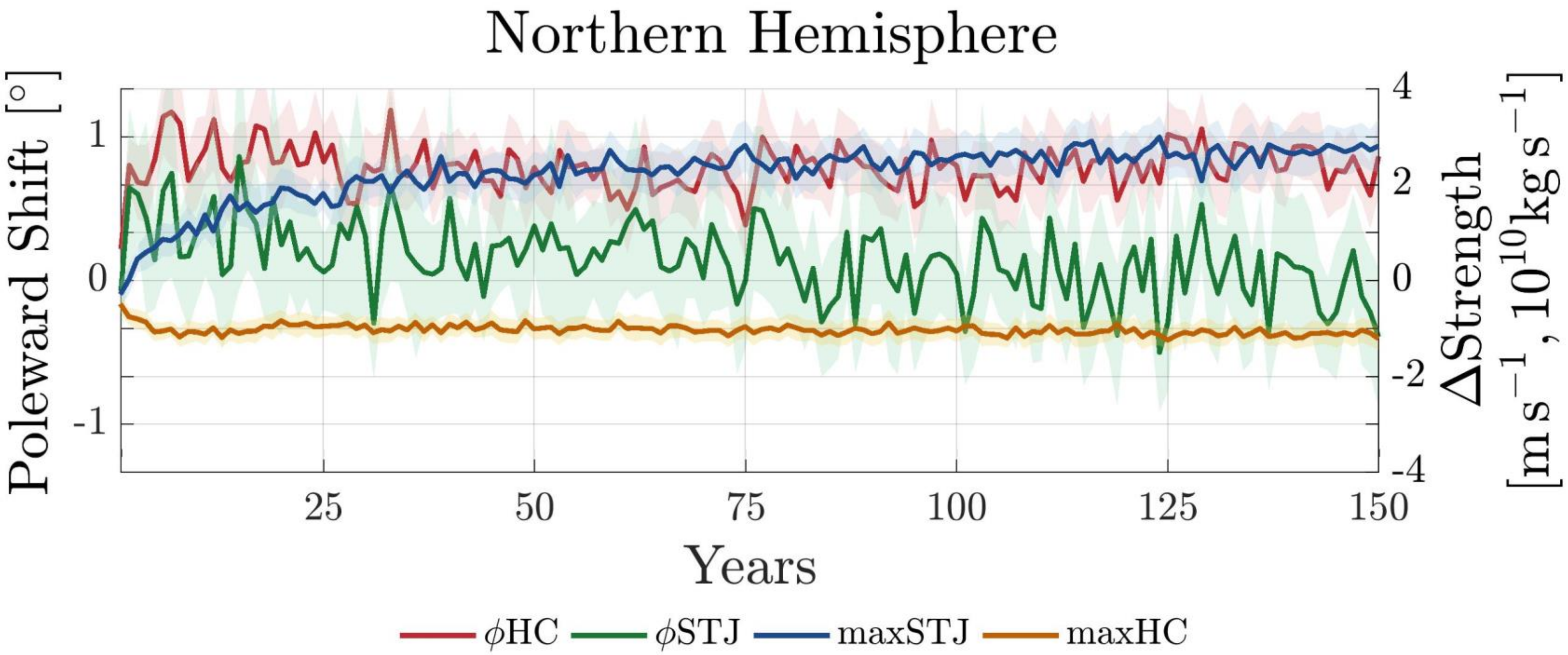
Menzel et al. 2019

	Shift/Change	τ
φHC	poleward	7
$\varphi(u'v')$	poleward	5
$uSTJ$	strengthening	40
$\partial T/\partial y$	strengthening	40

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

STJ strength:
- max meridional temperature gradient $\partial T/\partial y$

CMIP5: CO_2 Response

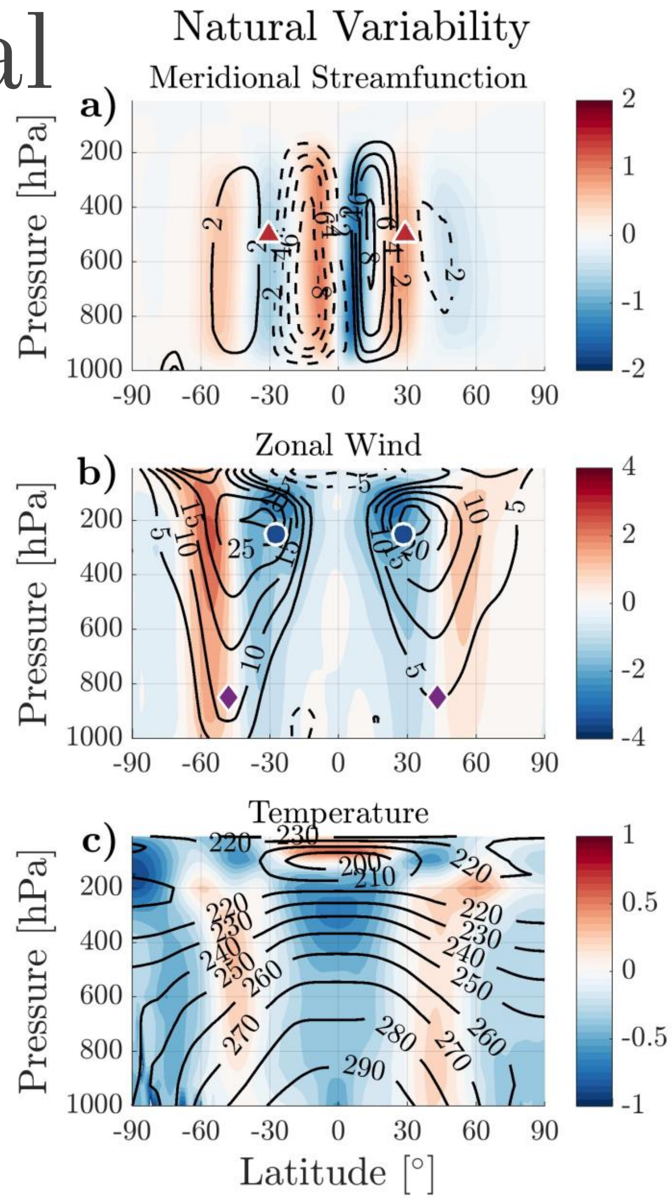


CMIP5: Interannual

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

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

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



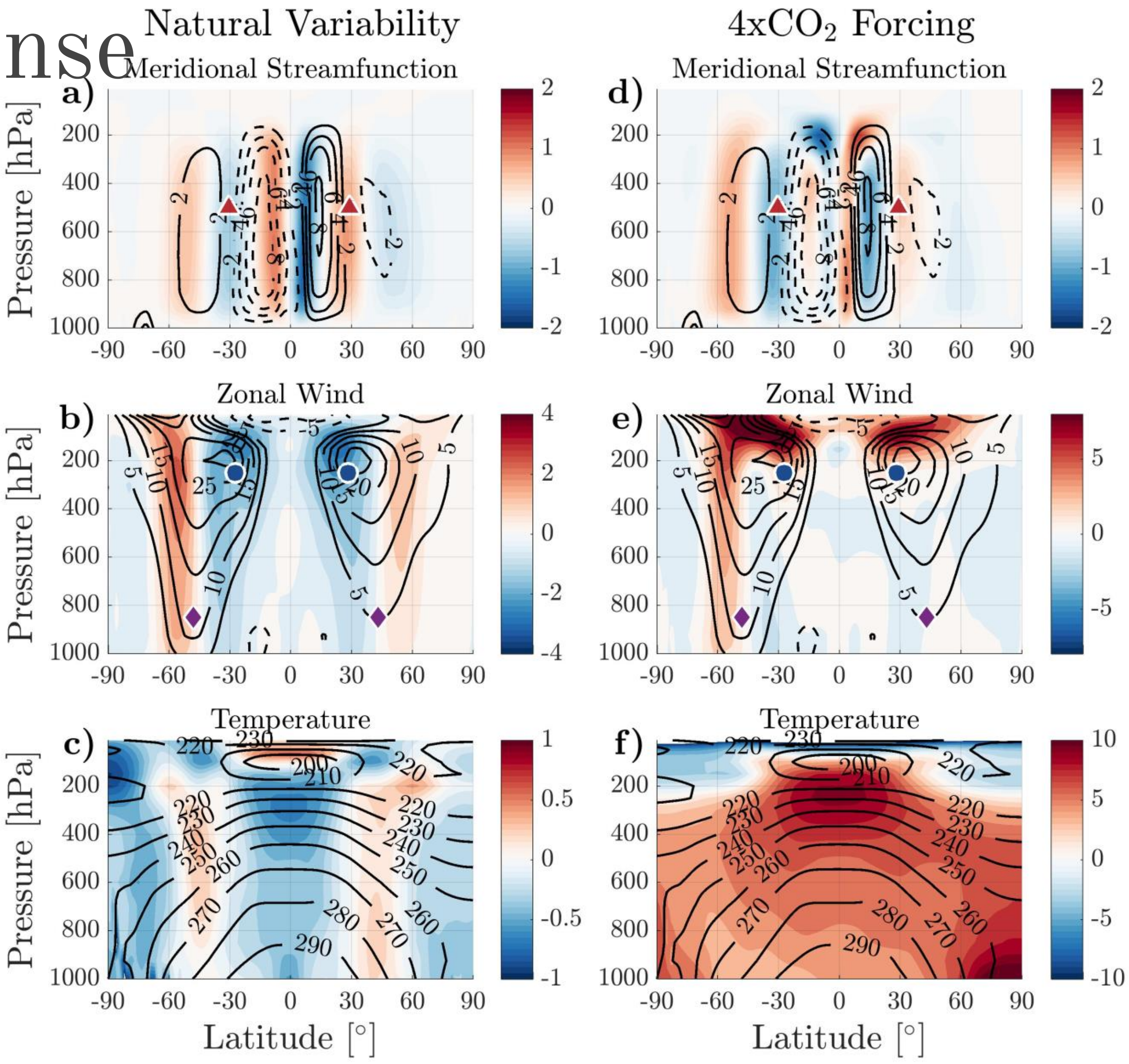
Menzel et al. 2019

CMIP5: CO_2 Response

HC:
- Expands (1.7°)
- Weakens ($0.4x10^{10}$ kg s^{-1})

EDJ:
- Shifts poleward (2.9°)
- Strengthens (1.6 m s^{-1})

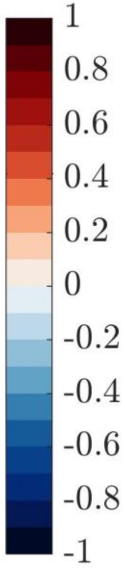
STJ
- Shifts poleward (0.4°)
- Strengthens (4.4 m s^{-1})



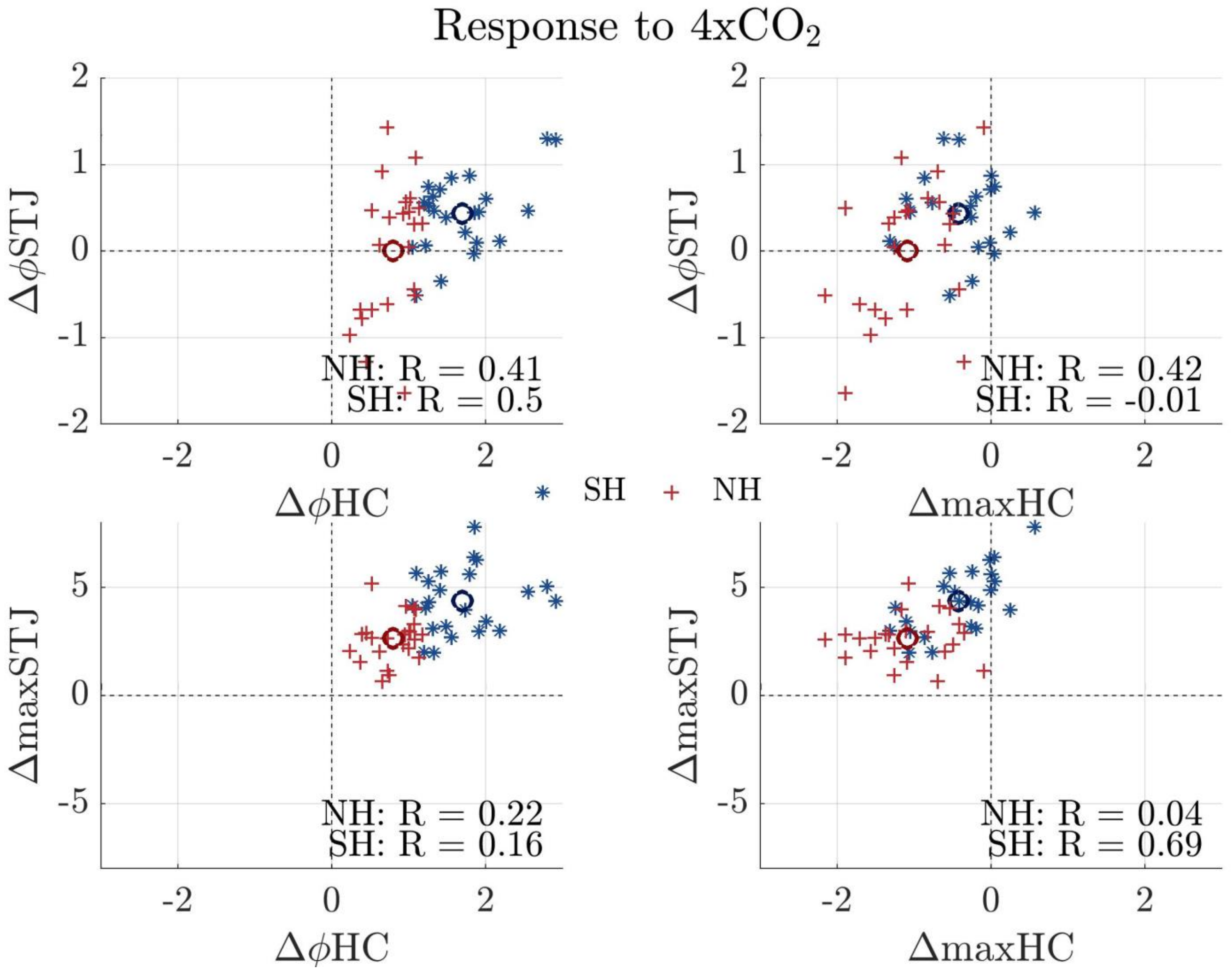
Menzel et al. 2019

CMIP5: Interannual Correlations

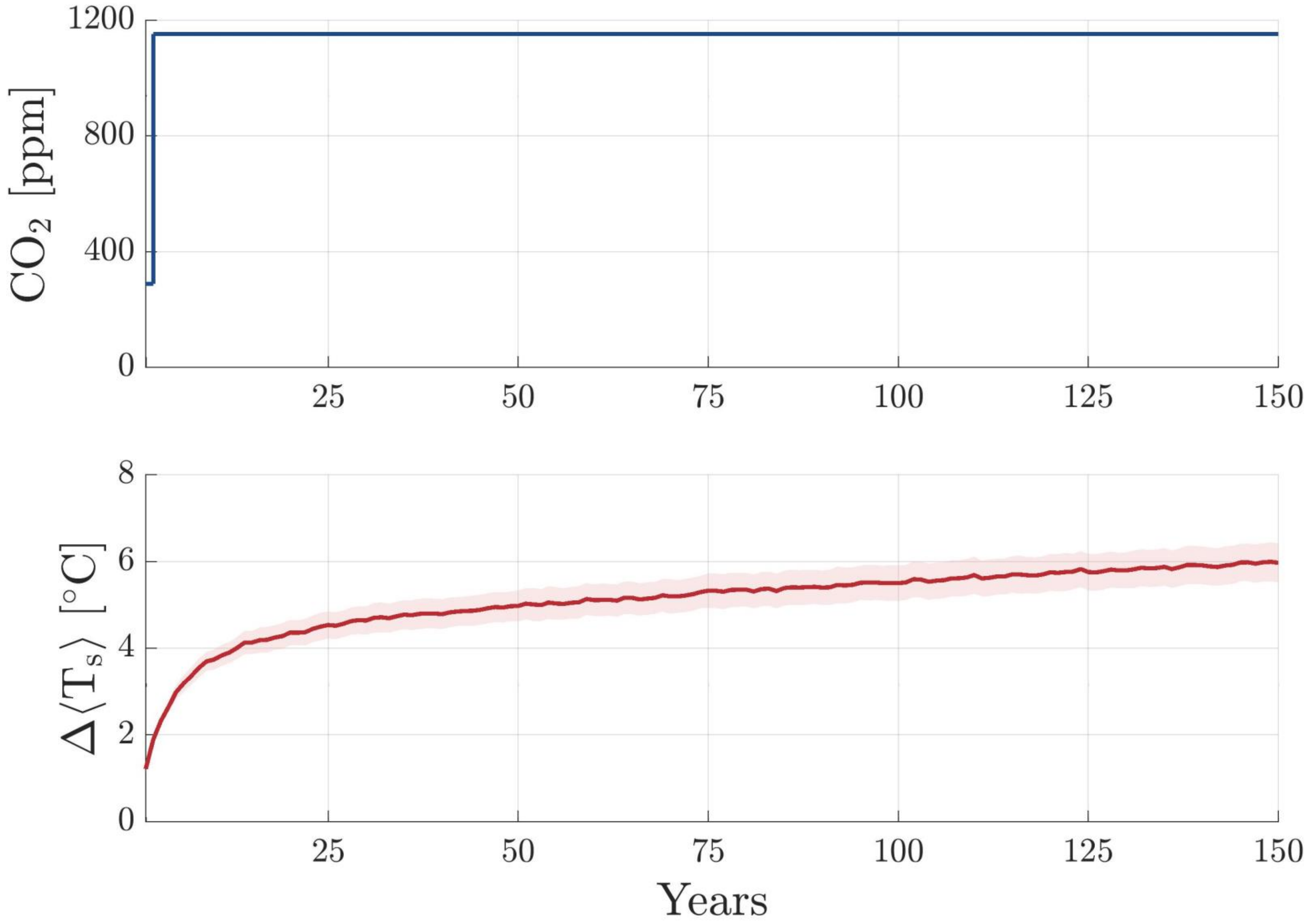
	Southern Hemisphere					Northern Hemisphere				
	ANN	DJF	MAM	JJA	SON	ANN	DJF	MAM	JJA	SON
ϕEDJ / ϕSTJ	**-0.02** (0.24)	**-0.18** (0.37)	**0.08** (0.26)	**-0.09** (0.08)	**-0.11** (0.2)	**0** (0.15)	**-0.01** (0.15)	**0.04** (0.13)	**0.31** (0.27)	**-0.17** (0.11)
ϕEDJ / maxSTJ	**0.01** (0.16)	**-0.39** (0.35)	**0.03** (0.16)	**0.09** (0.15)	**0.17** (0.15)	**-0.38*** (0.14)	**-0.4*** (0.12)	**-0.31** (0.17)	**-0.21** (0.27)	**-0.32*** (0.13)
maxEDJ / ϕSTJ	**0.08** (0.15)	**0.04** (0.29)	**0.03** (0.12)	**0.2** (0.13)	**0.01** (0.17)	**0.17** (0.19)	**0.27*** (0.12)	**0.12** (0.17)	**0.31*** (0.14)	**0.19** (0.15)
maxEDJ / maxSTJ	**-0.11** (0.14)	**-0.25** (0.13)	**-0.08** (0.12)	**-0.21** (0.16)	**-0.12** (0.2)	**-0.28*** (0.25)	**-0.2** (0.21)	**-0.08** (0.19)	**-0.06** (0.2)	**-0.21*** (0.11)



CMIP5: CO_2 Response



CMIP5: CO_2 Response



Dry Dynamical Core

GFLD Spectral Core

Equilibrium Temperature (Held and Suarez 1994)

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

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Tropical Warming (Sun et al. 2013)

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

Narrow	*Broad*
$\phi_0 = 10^\circ$	$\phi_0 = 10^\circ$

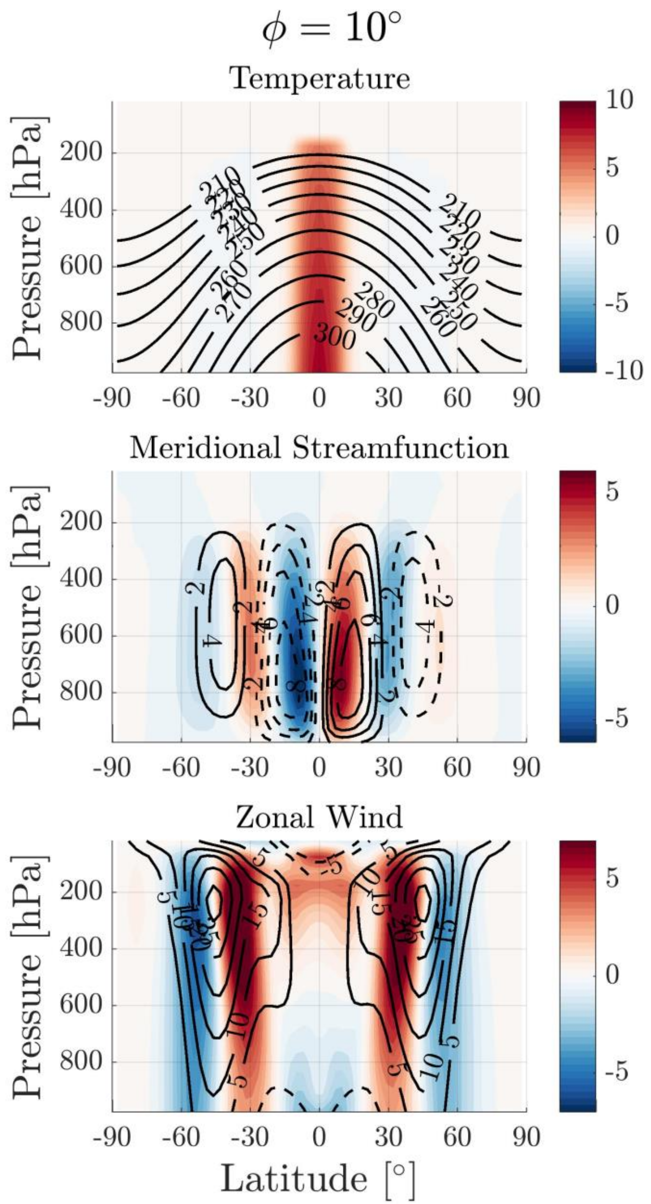
Warming Width

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(10^{10}) kg s^{-1})

EDJ: Shifts equatorward (4.8°)

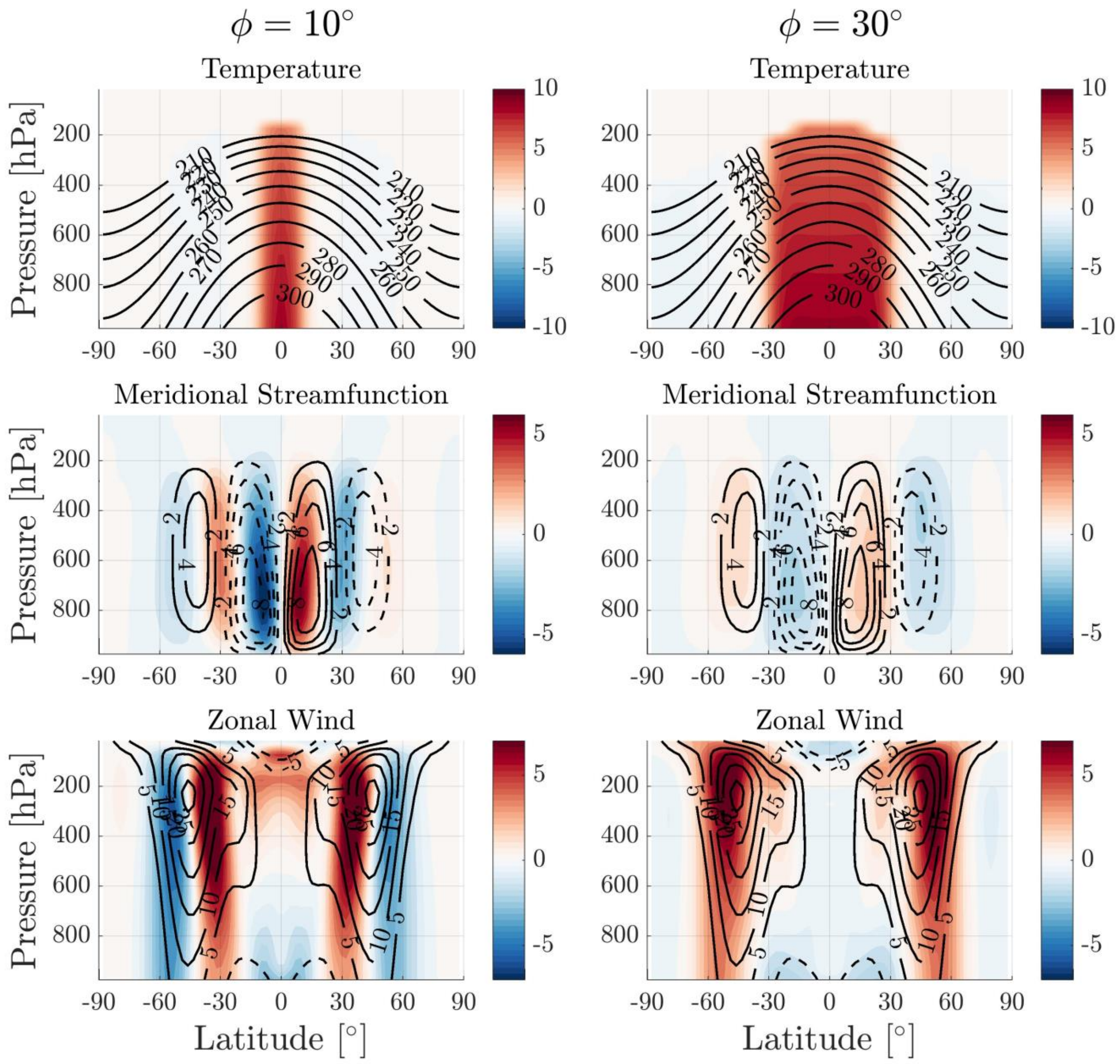
STJ: Strengthens (4.5 m s^{-1})

Broad Forcing

HC: Slight expansion (1.1°)

EDJ: Shifts poleward (1.7°)

STJ: Strengthens (3.9 m s^{-1})



Warming Width

Narrow Forcing

HC: Contracts, strengthens

EDJ: Shifts equatorward

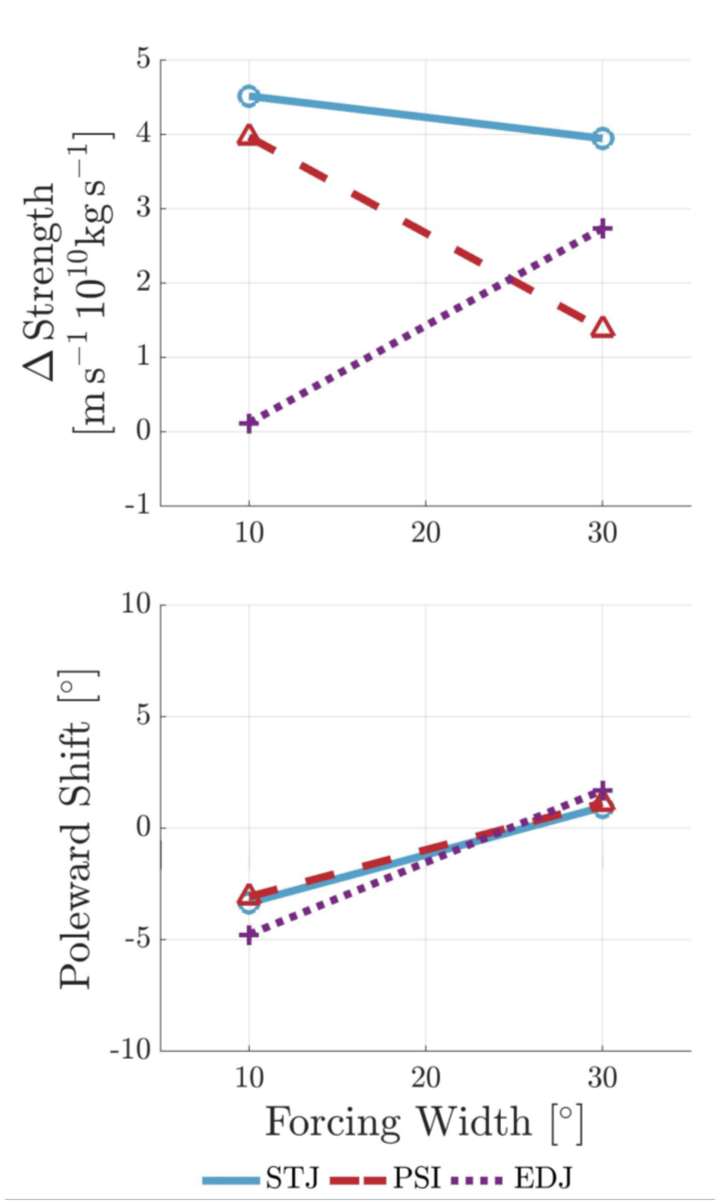
STJ: Strengthens

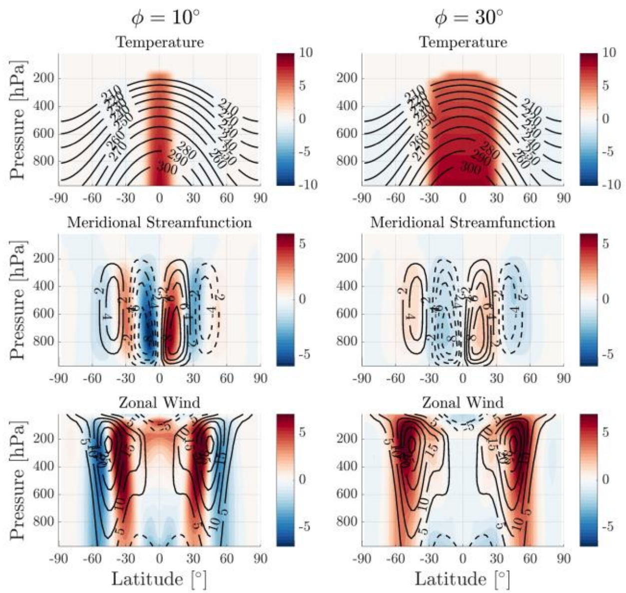
Broad Forcing

HC: Slight expansion

EDJ: Shifts poleward

STJ: Strengthens

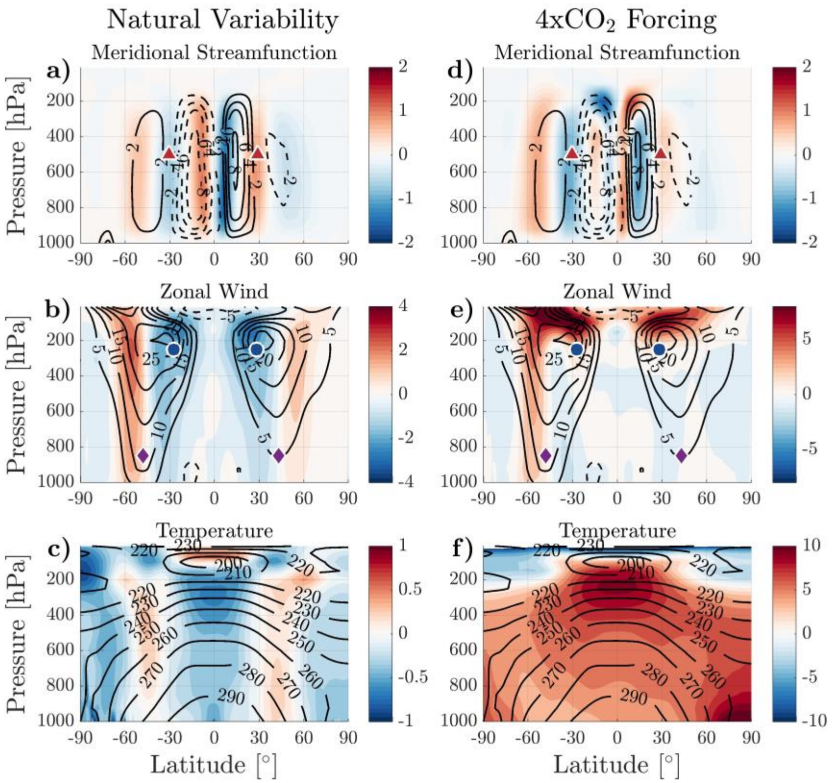




Key Takeaways

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

	Southern Hemisphere					Northern Hemisphere				
	ANN	DJF	MAM	JJA	SON	ANN	DJF	MAM	JJA	SON
ϕHC maxSTJ	**-0.19** (0.16)	**-0.34** (0.26)	**-0.14** (0.16)	**-0.25*** (0.13)	**-0.1** (0.17)	**-0.39*** (0.14)	**-0.3*** (0.13)	**-0.52*** (0.13)	**-0.29*** (0.18)	**-0.15** (0.15)



2. *The interannual relationship between HC edge and STJ strength is the opposite sign as the response to increased atmospheric CO_2*

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*

Menzel, Molly E., Darryn Waugh, and Kevin Grise (2019). "Disconnect between Hadley Cell and Subtropical Jet variability and response to increased CO_2." *Geophysical Research Letters*.

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

Run	Perturbation		Eddy permitting
	$\Delta\langle T_s\rangle$	$\Delta\phi_T$	
1	1.5K	5°-45°	yes
2	3K	5°-45°	yes
3	1.5K	5°-45°	no
4	-1.5K	60°-90°	yes

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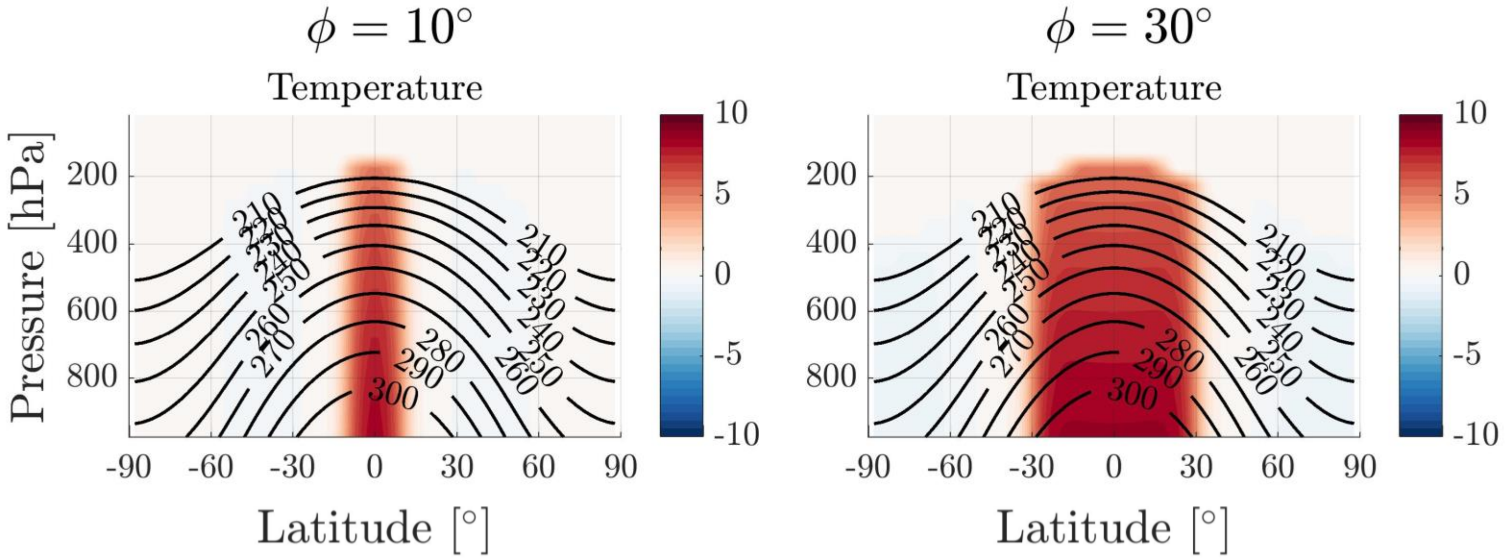

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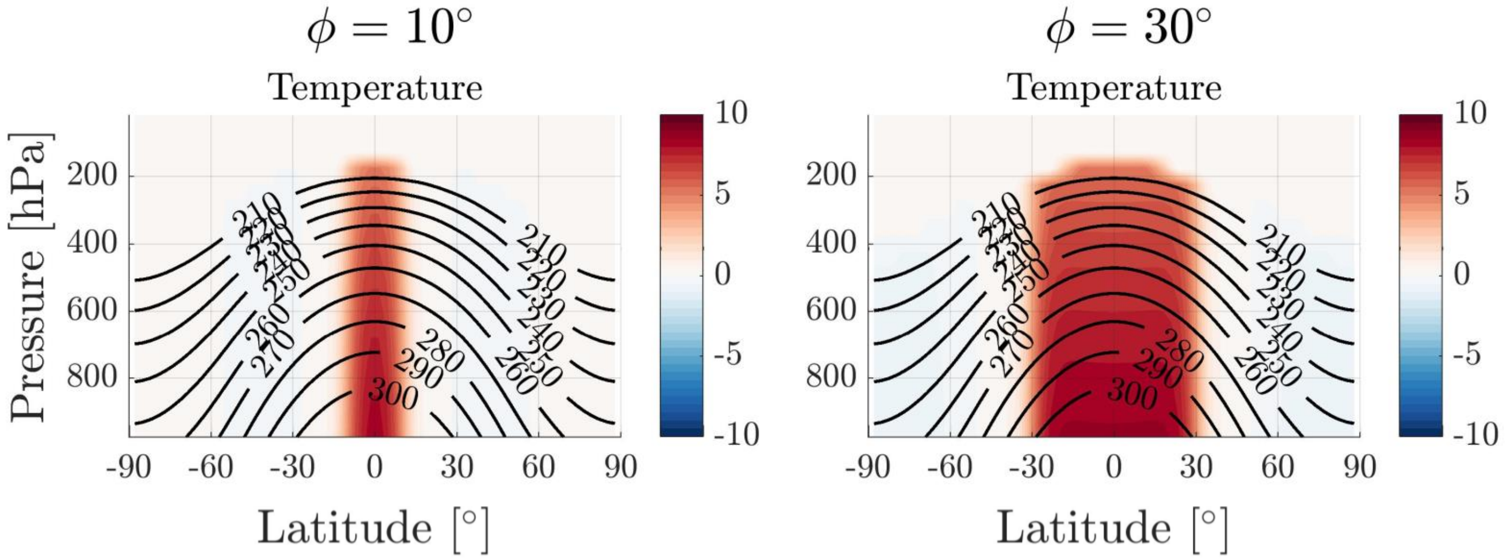
ANALYSIS:
Momentum Budget
- Role of eddy momentum fluxes



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Questions?

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ANALYSIS:
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