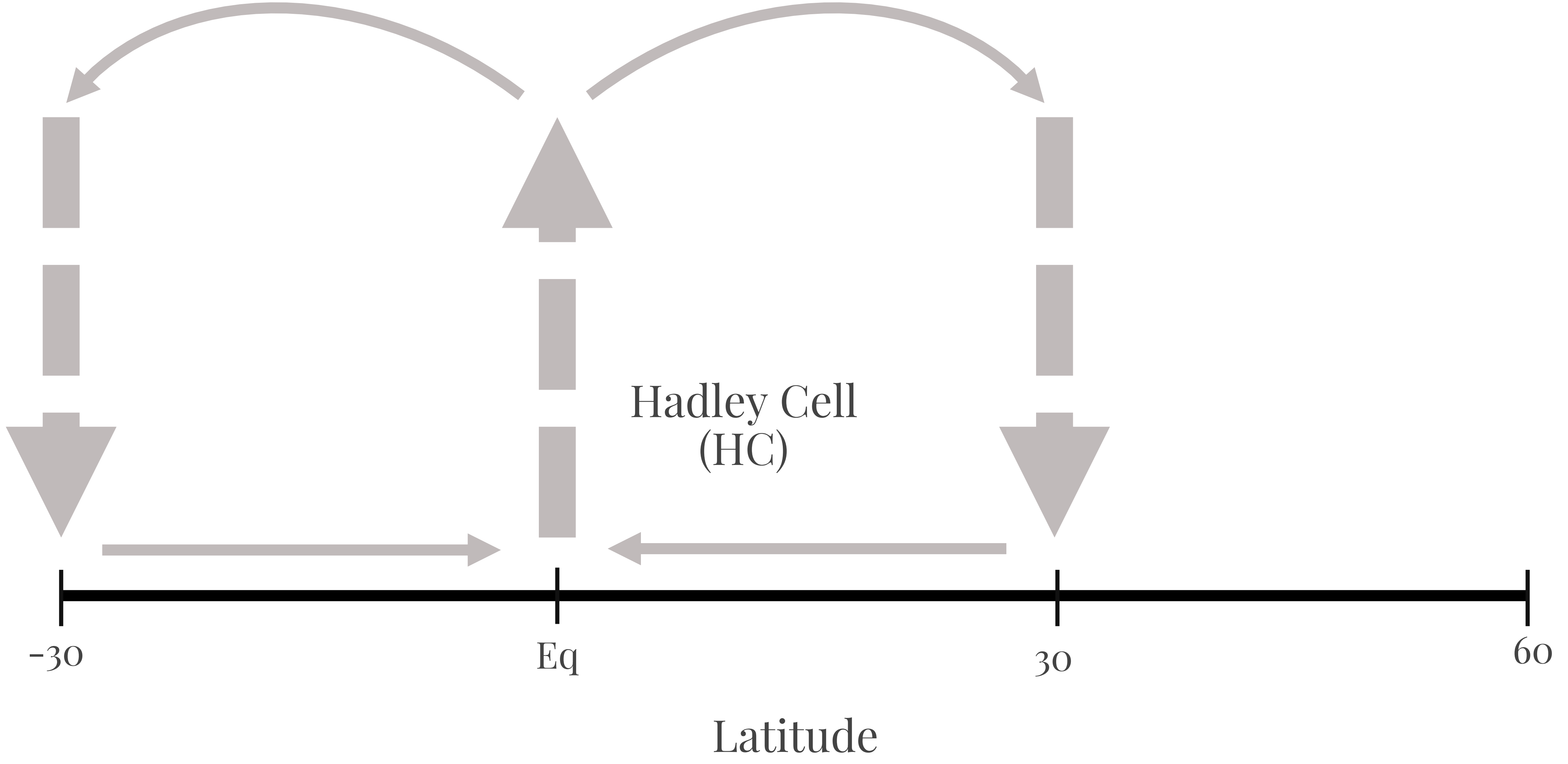
Revisiting the Coupled Behavior of the Subtropical Jet and Hadley Cell

MOLLY MENZEL
January 26, 2021
Advisor: Prof. Darryn Waugh
Johns Hopkins University

Introduction

Atmospheric General Circulation



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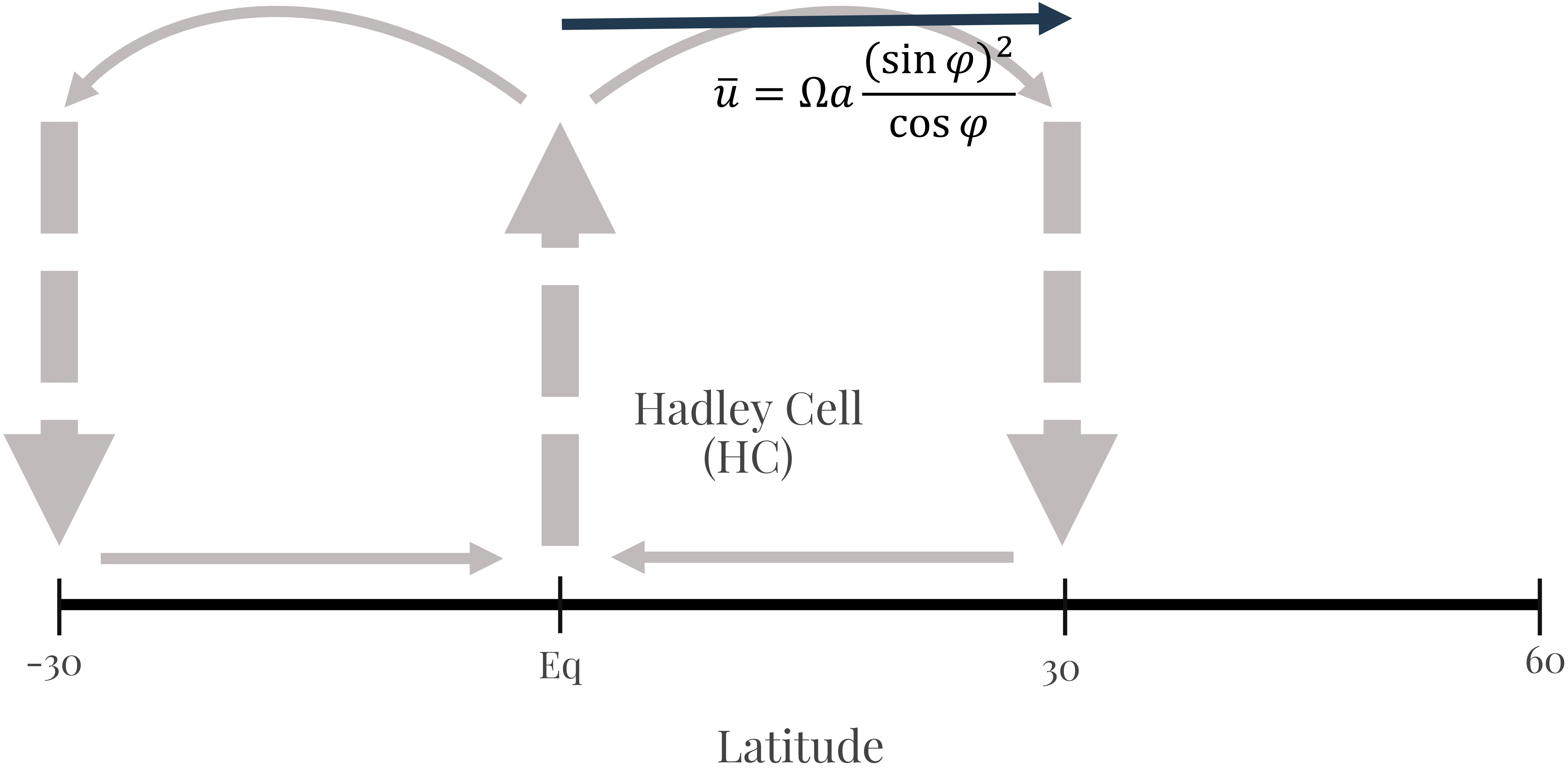

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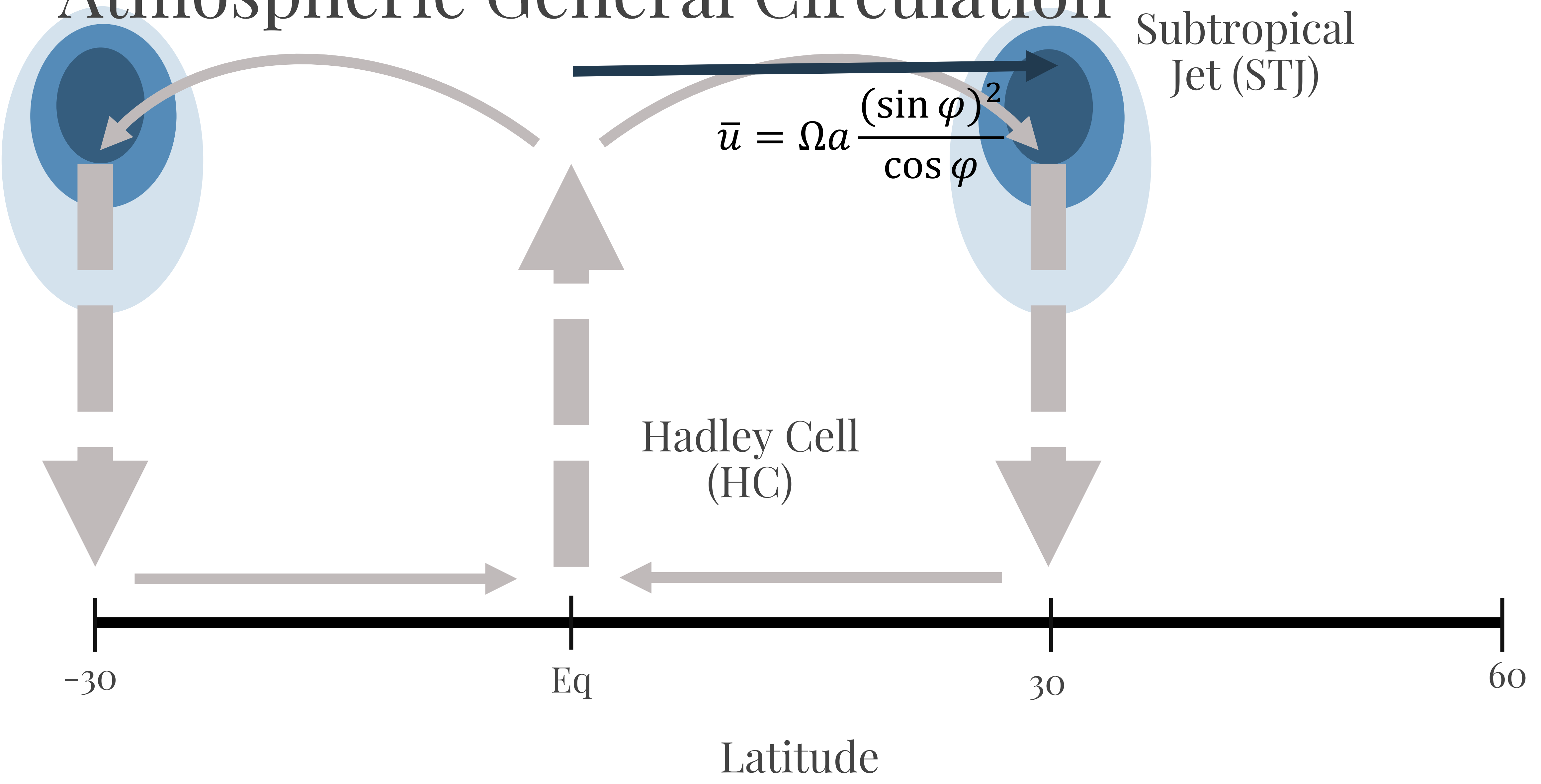

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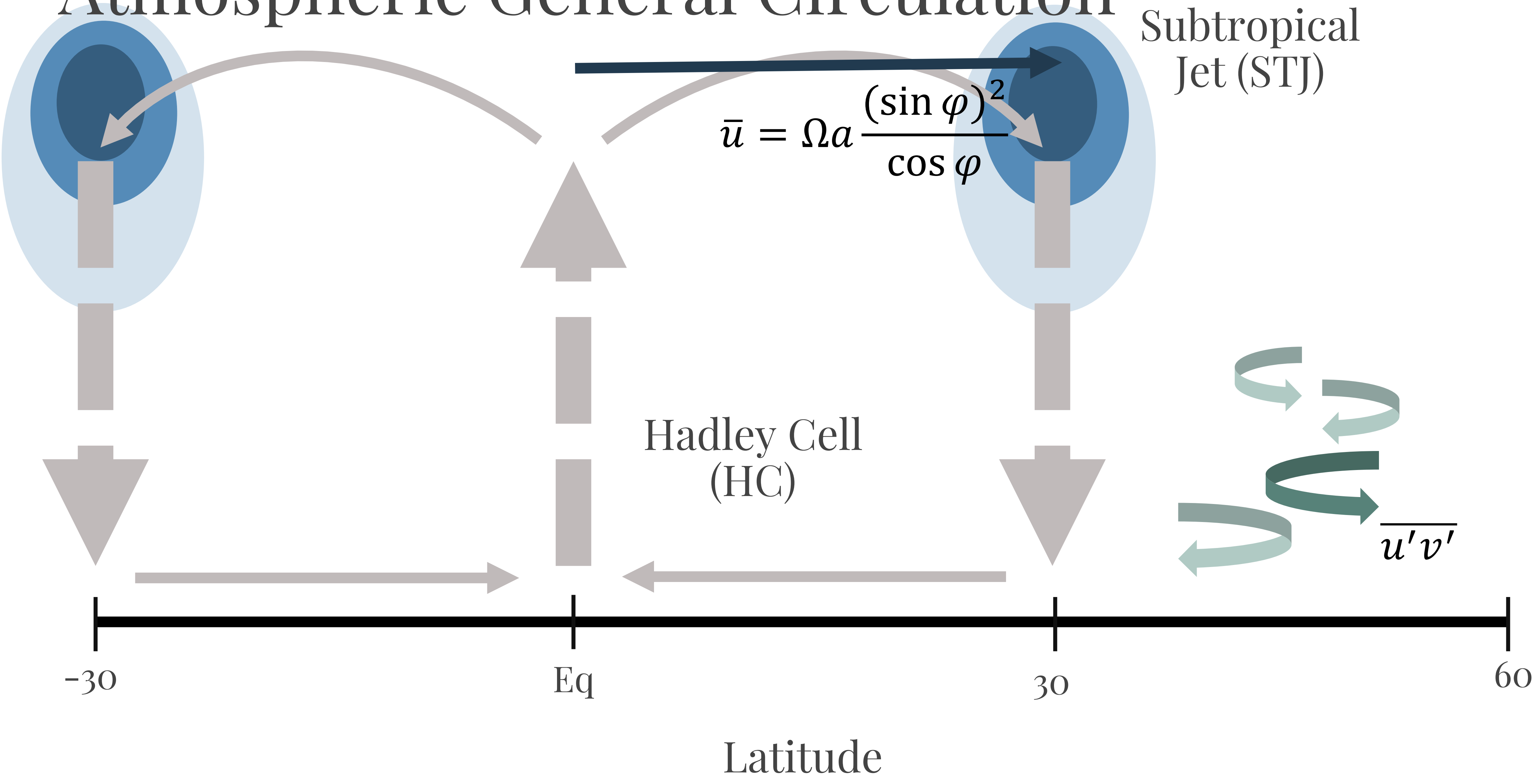

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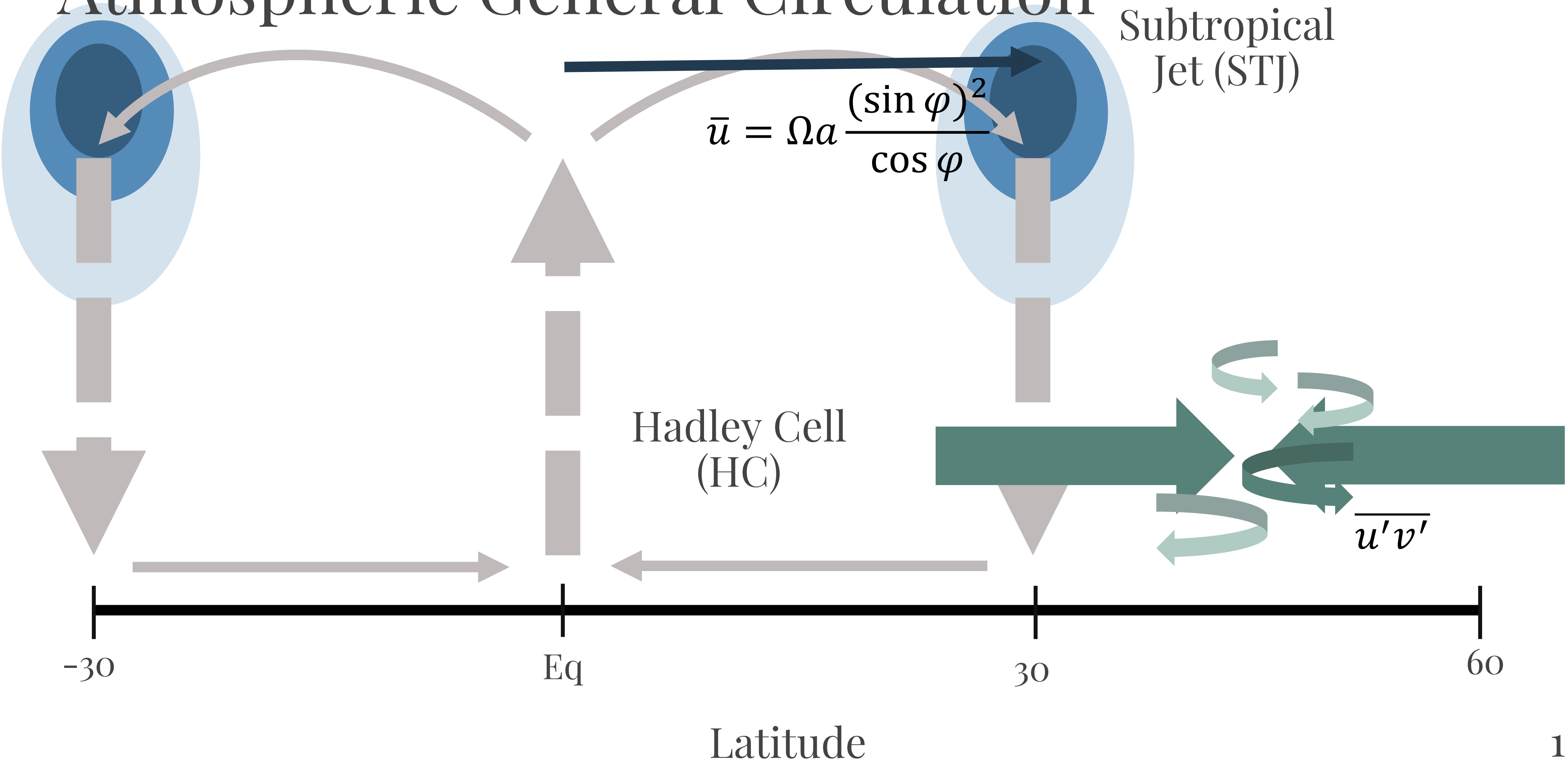

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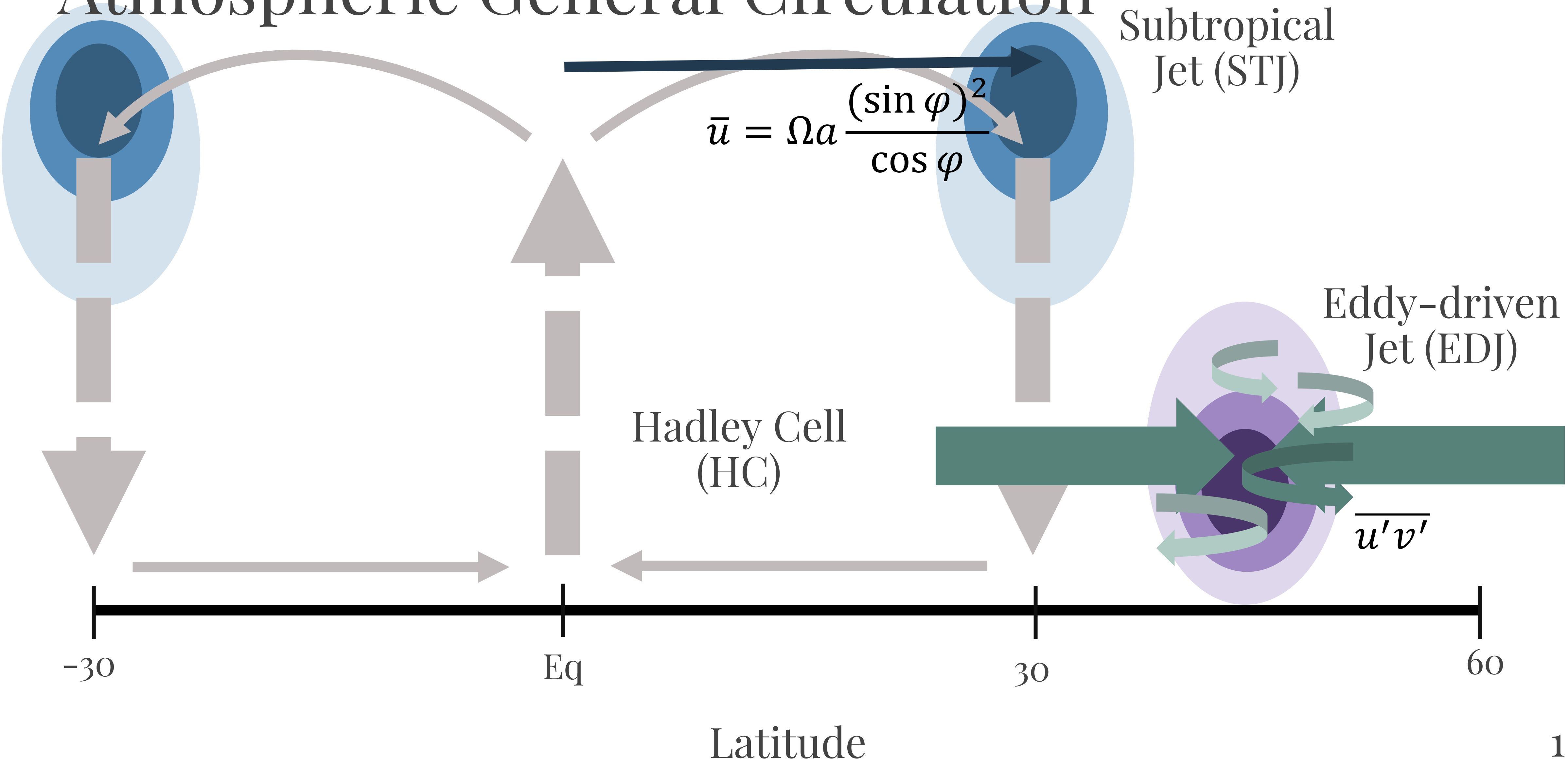

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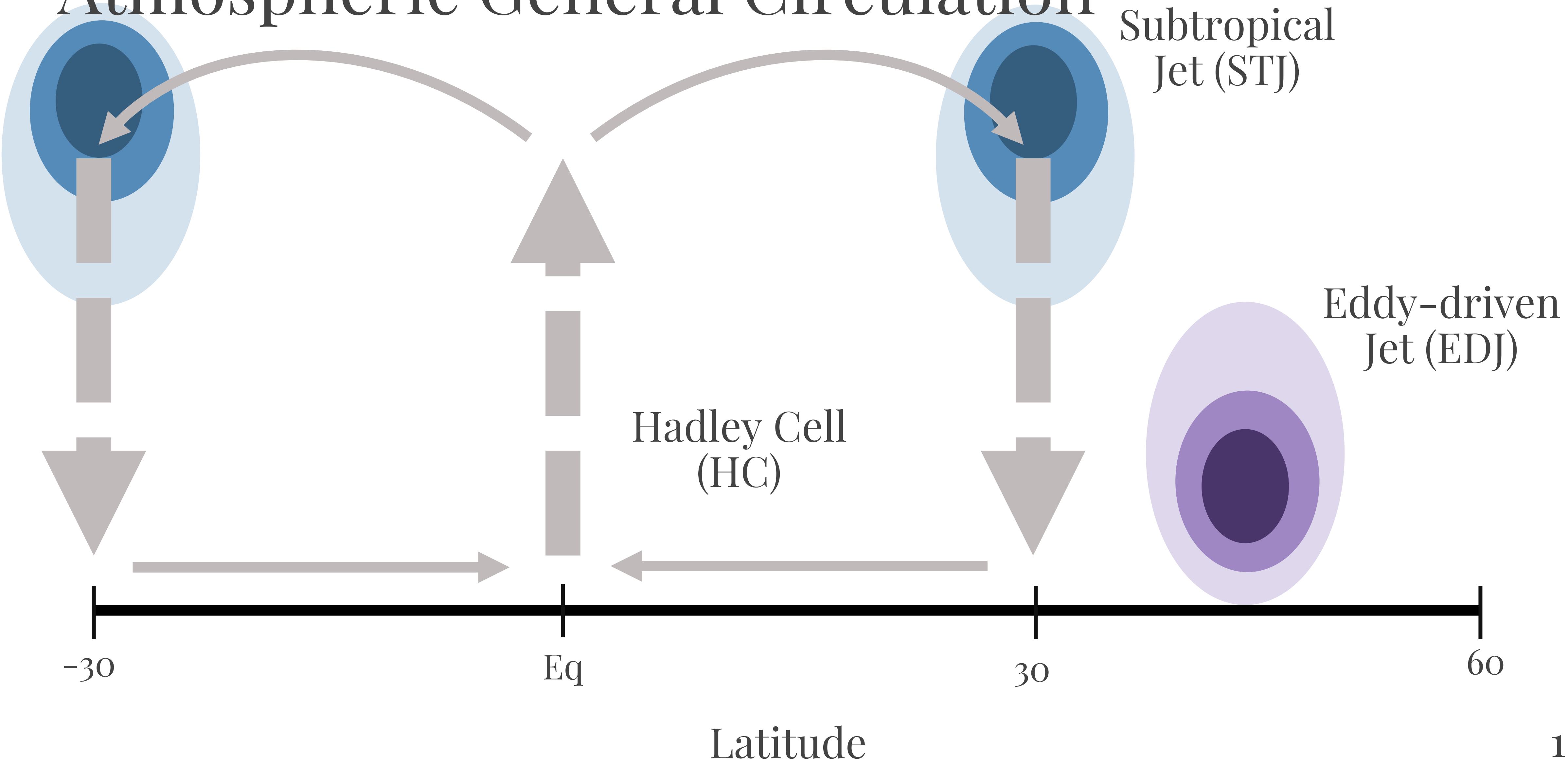

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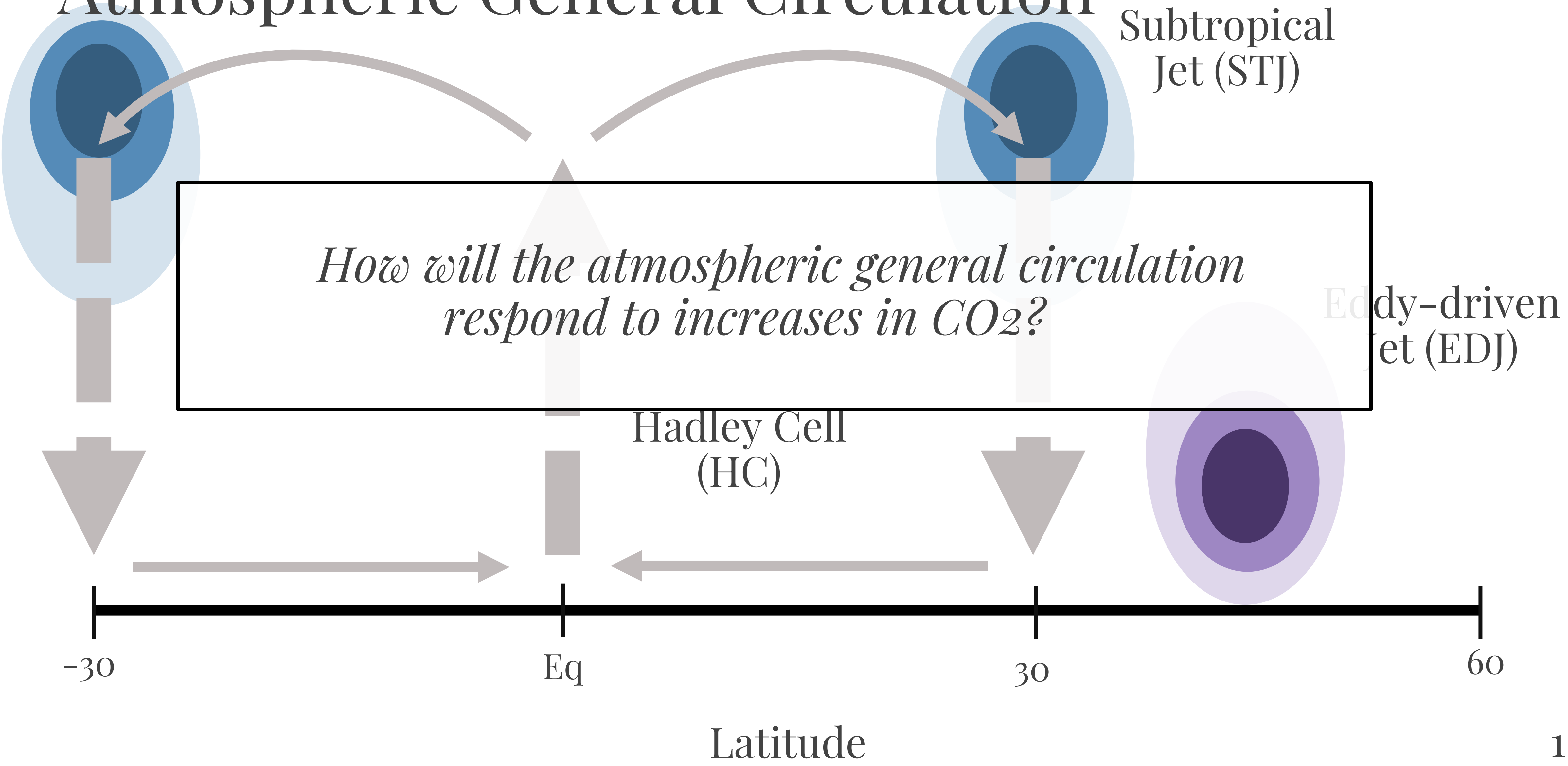


How will the atmospheric general circulation respond to increases in CO_2?

Tropical Expansion

Response to CO2 Forcing

December 2014 Physics Today

The changing width of Earth's tropical belt

Thomas Birner, Sean M. Davis, and Dian J. Seidel

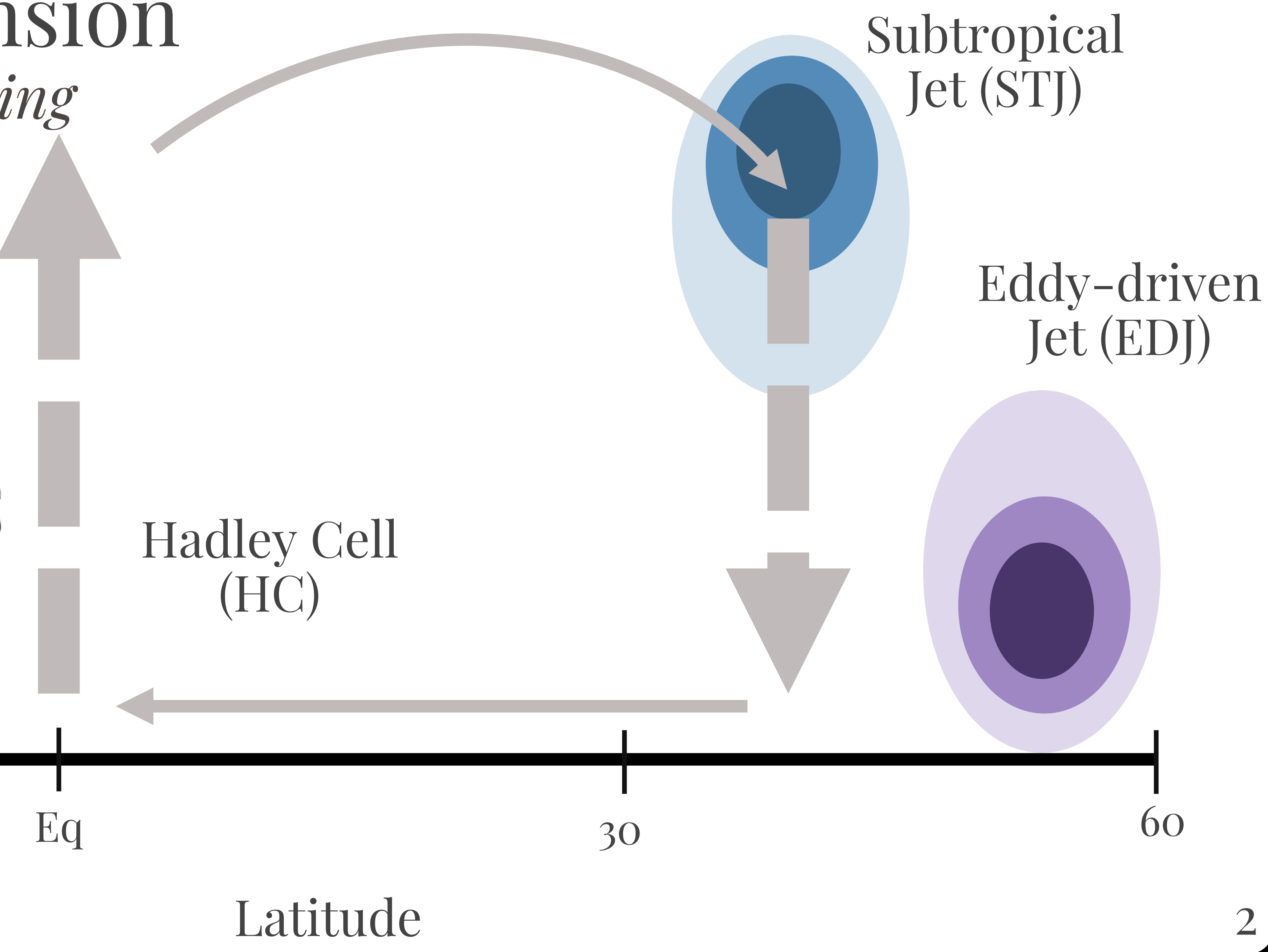
THE MYSTERY OF THE EXPANDING TROPICS

AS EARTH'S DRY ZONES SHIFT RAPIDLY POLEWARDS, RESEARCHERS ARE SCRAMBLING TO FIGURE OUT THE CAUSE — AND CONSEQUENCES.

BY OLIVE HEFFERNAN

PROGRESS ARTICLE

Widening of the tropical belt in a changing climate



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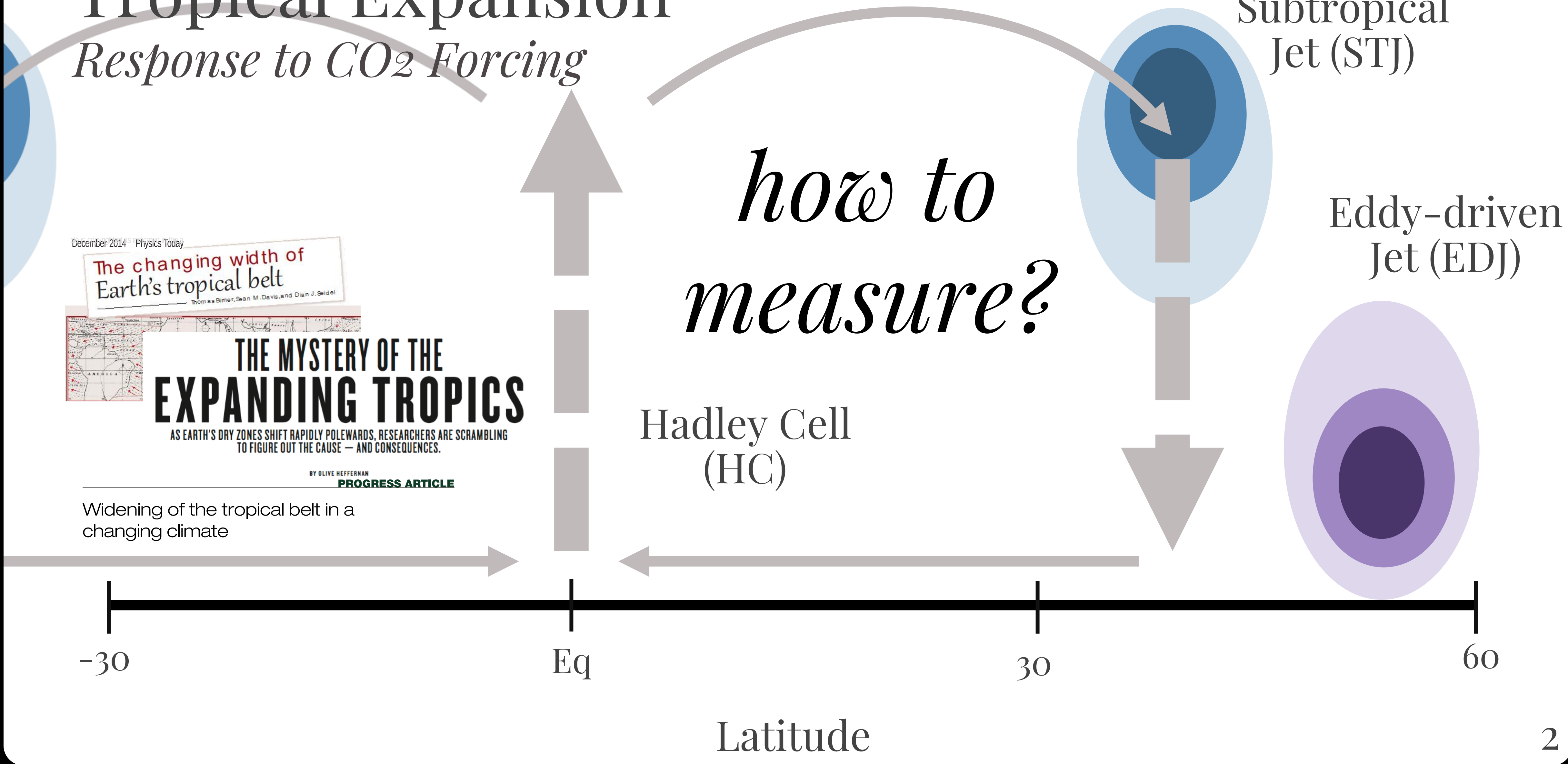
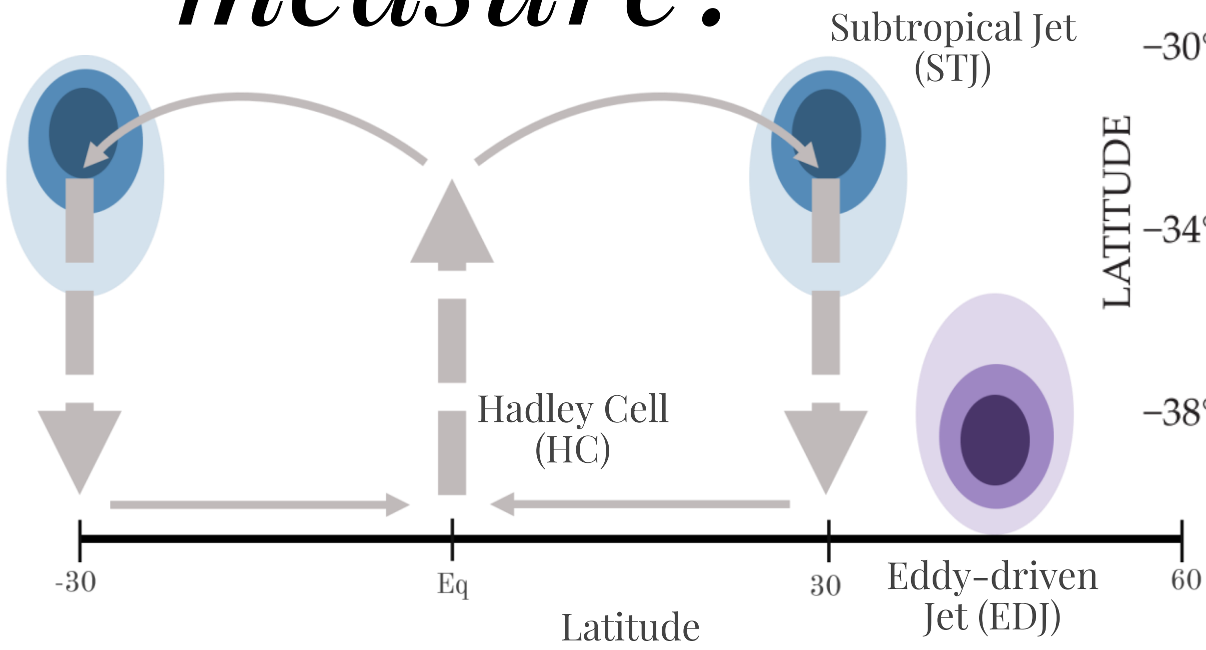
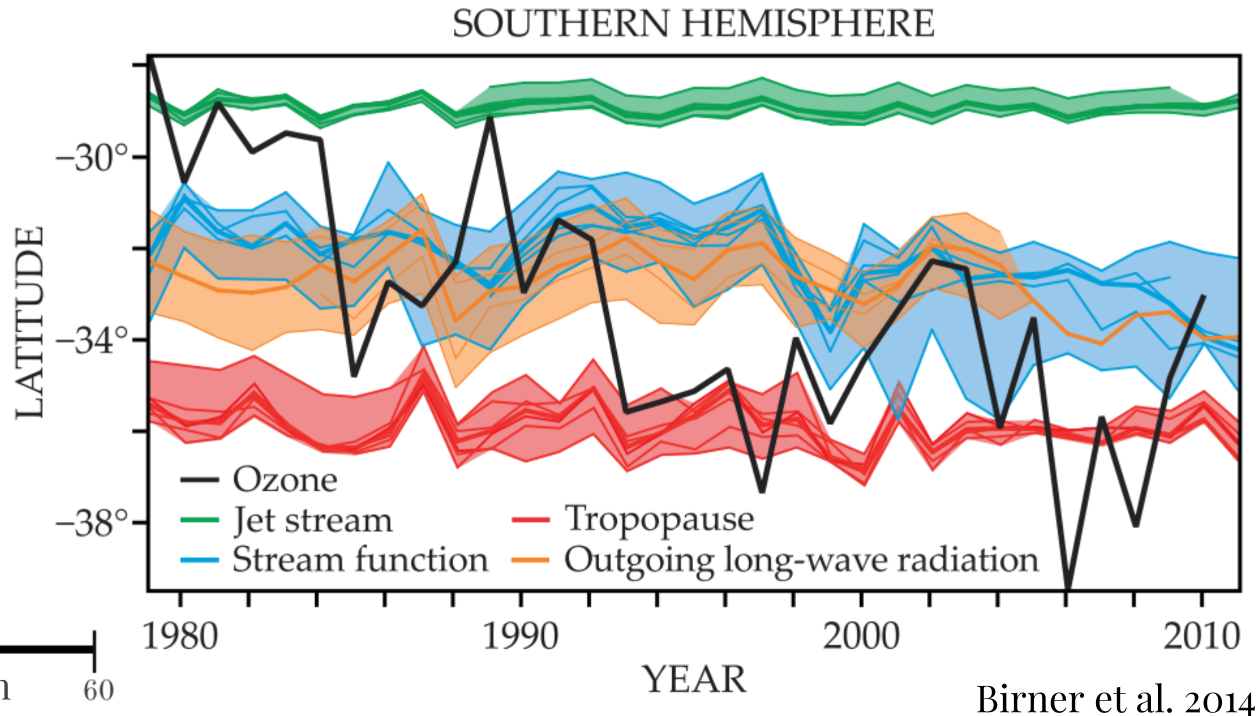


Tropical Expansion

Response to CO2 Forcing

how to measure?





Birner et al. 2014

Tropical Expansion

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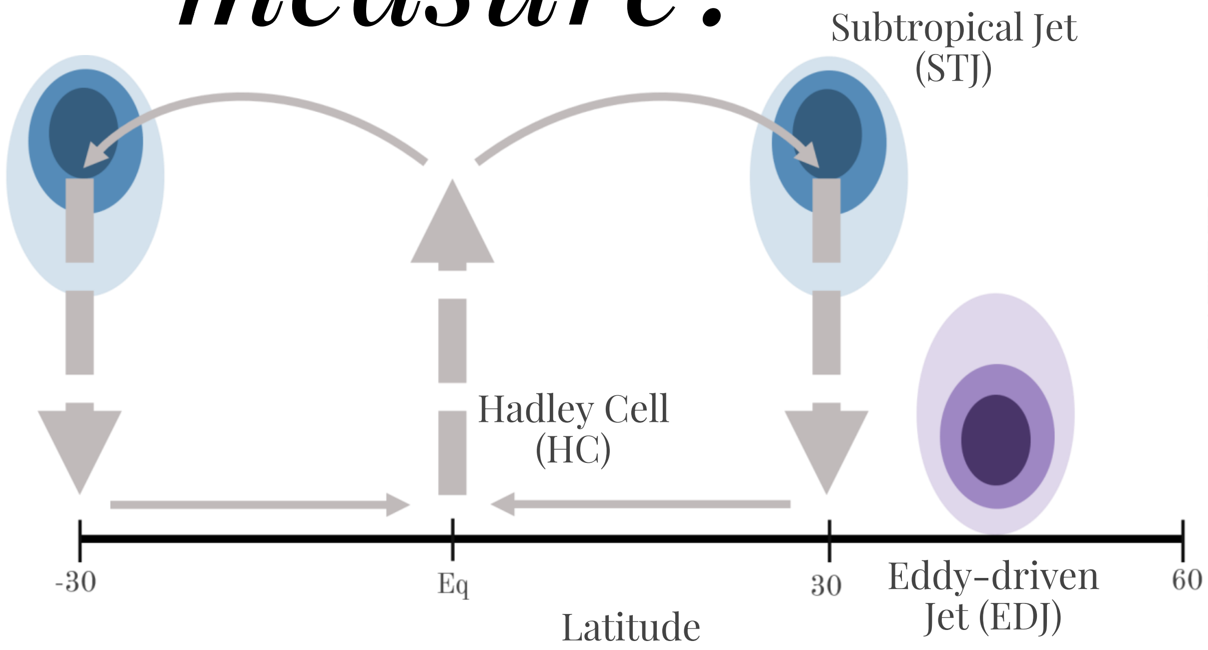
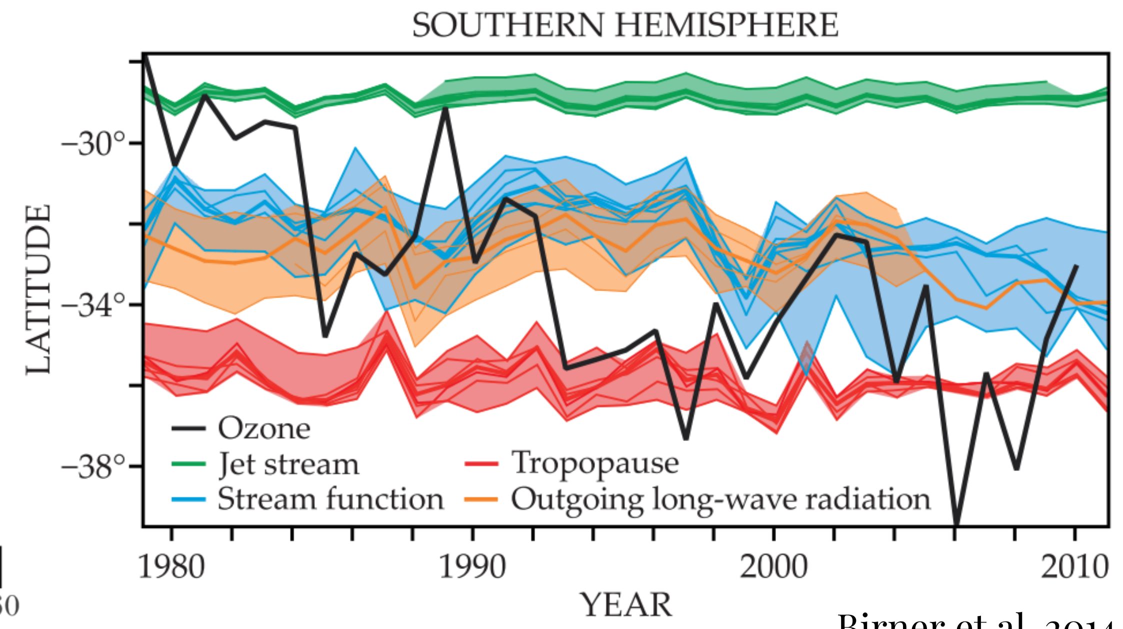
Current understanding of atmospheric general circulation: the subtropical jet (STJ) should be coupled to the Hadley cells (HC)...





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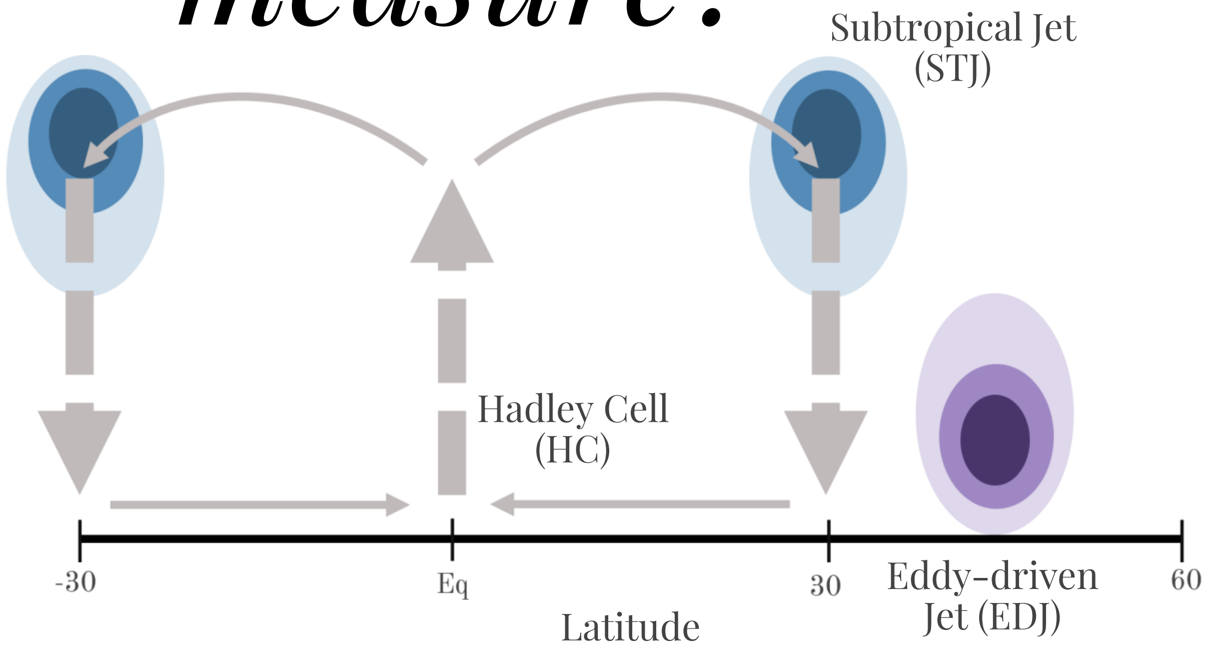

... reanalysis products and models do not support this!

Waugh et al. (2018)
Davis & Birner (2017)
Solomon et al. (2017)

Tropical Expansion

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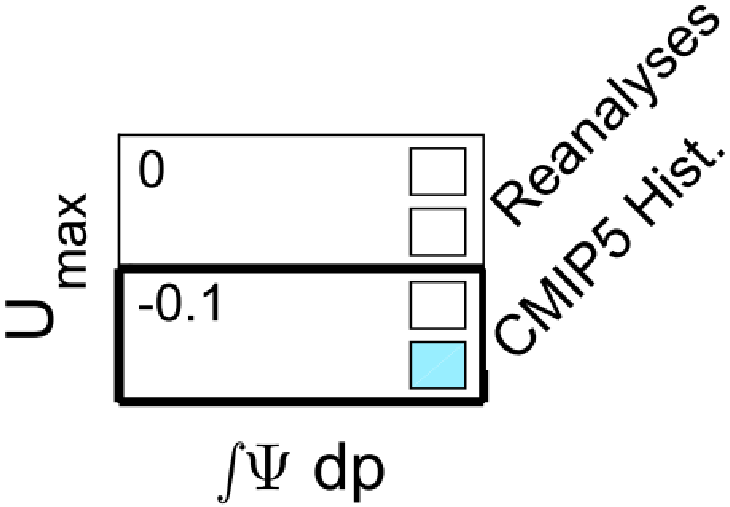

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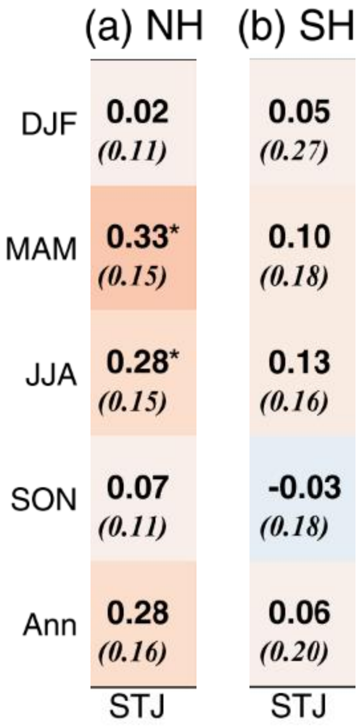

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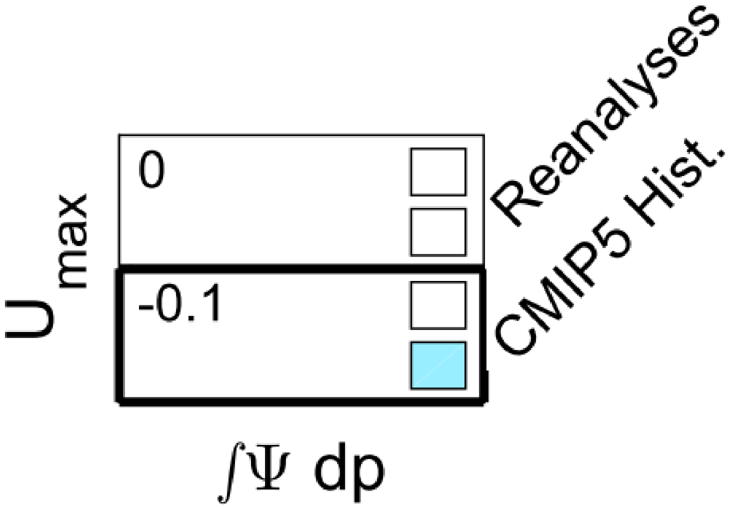

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Tropical Expansion

Response to CO2 Forcing

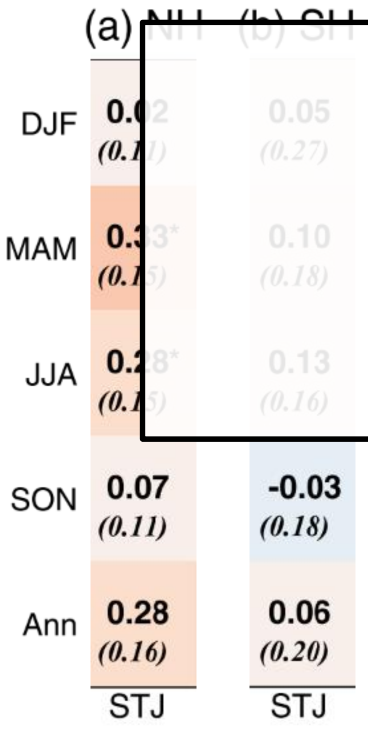
Current understanding of atmospheric general circulation: the subtropical jet (STJ) should be coupled to the Hadley cells (HC)...

Knowledge Oversight!

Do we truly understand atmospheric circulation?

...analysis products and models do not support this!

Waugh et al. (2018)
Davis & Birner (2017)
Solomon et al. (2017)



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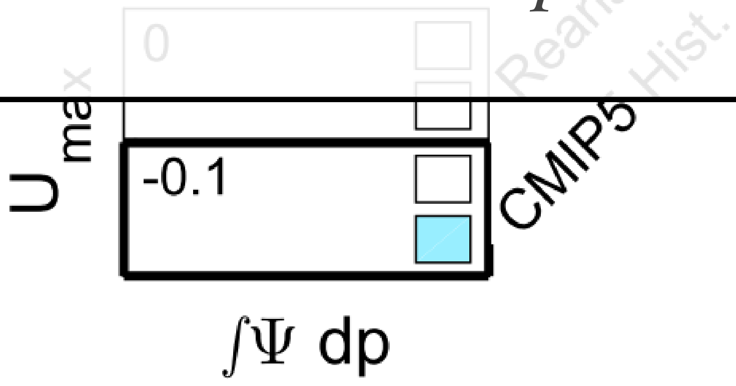
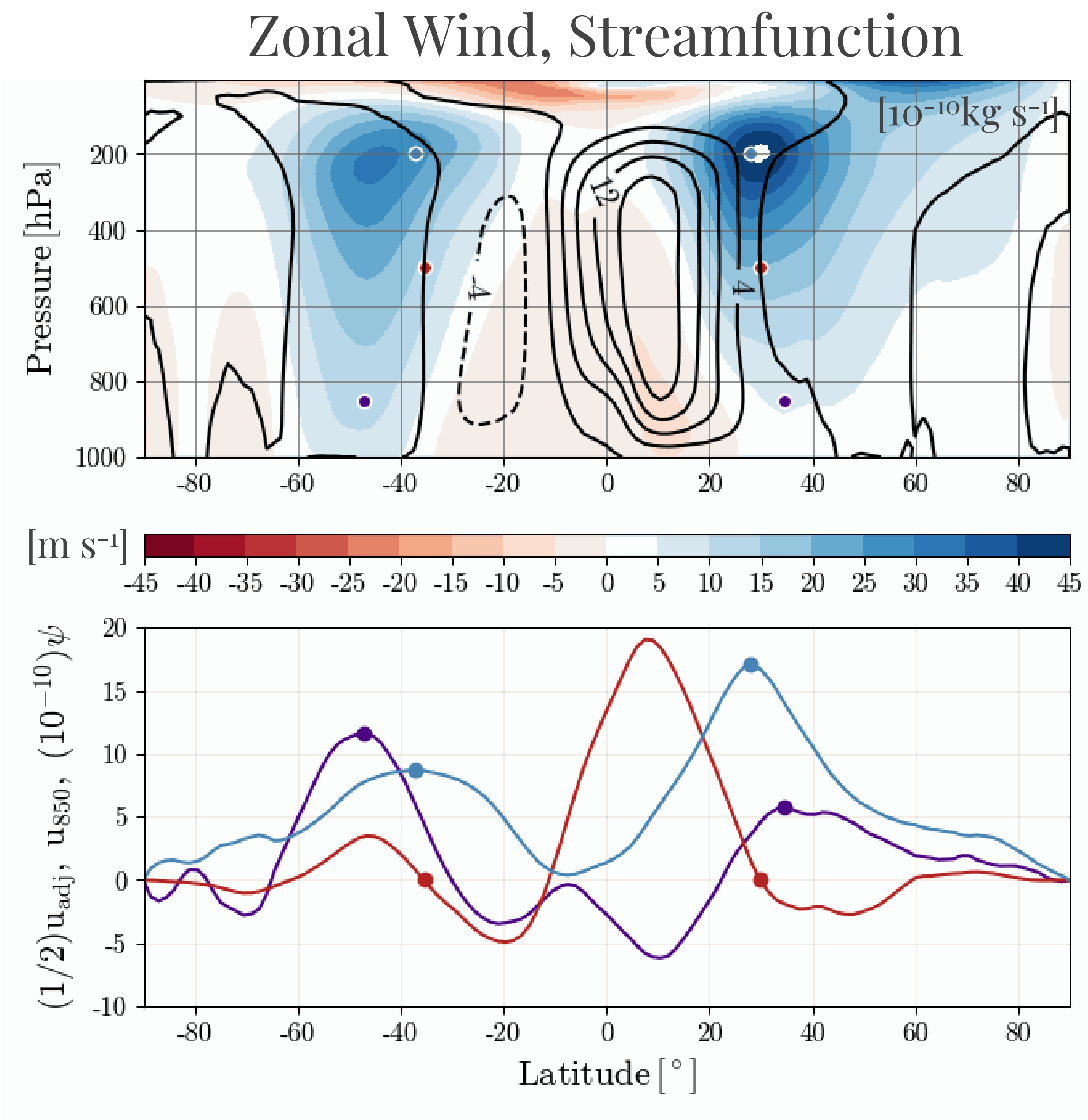


Davis & Birner 2017

Circulation Metrics

Hadley Cell (HC)

- "PSI500"
  $\varphi HC = \varphi(\psi_{500\,hPa} = 0)$



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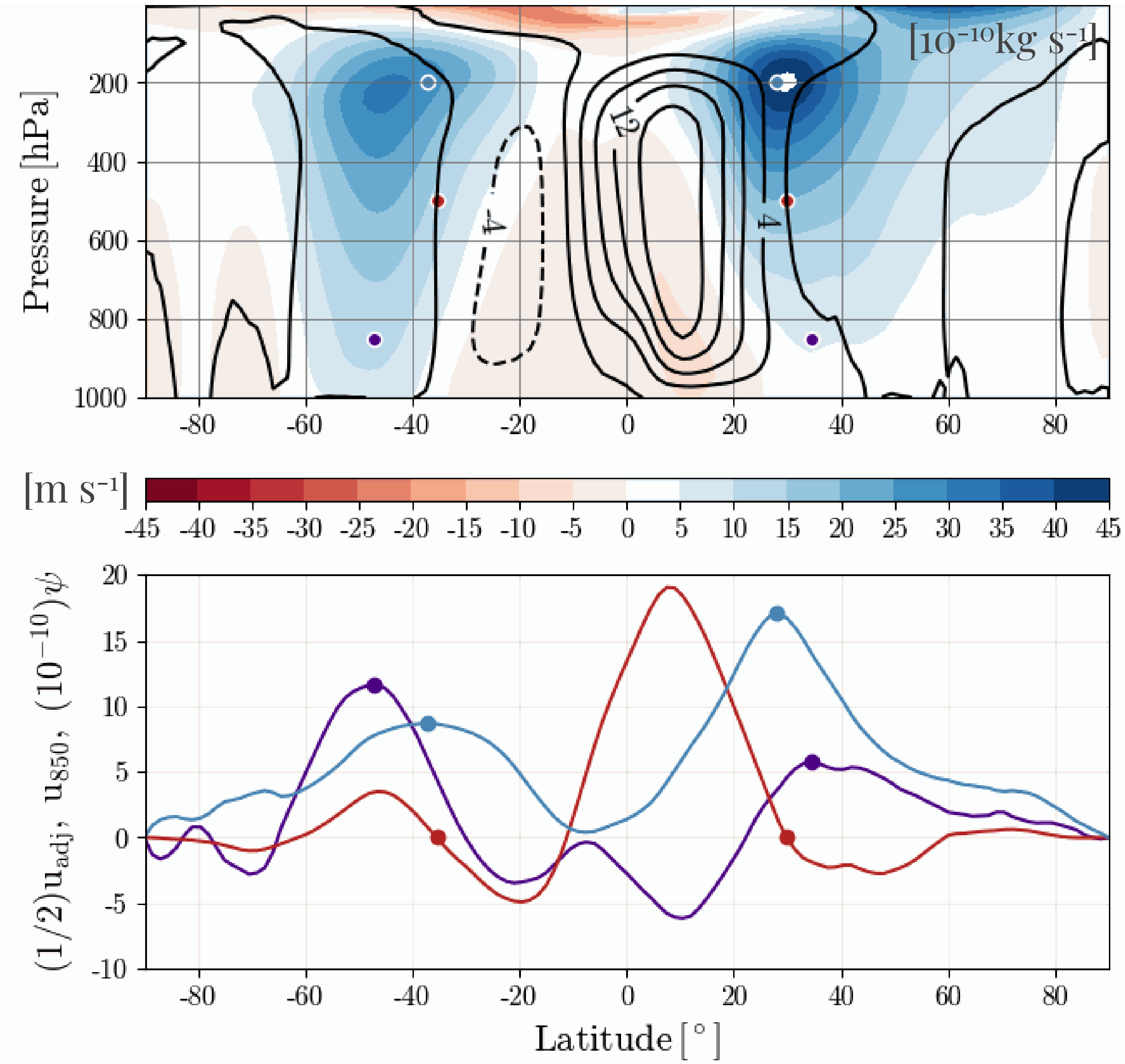
Eddy-Driven Jet (EDJ)

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

Zonal Wind, Streamfunction



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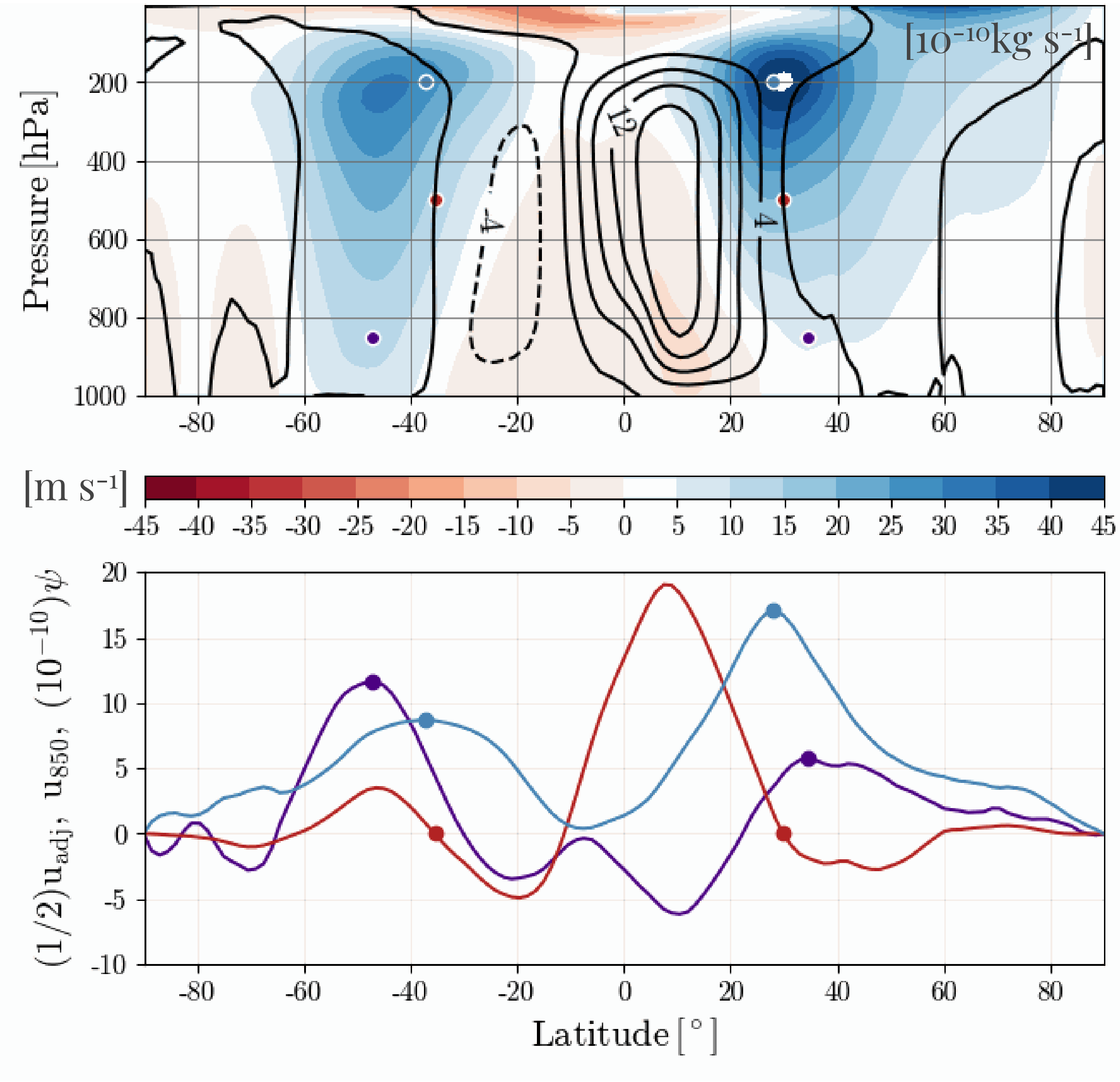
Subtropical Jet (STJ)

$$\varphi STJ = \varphi(max(\Delta u))$$
$$uSTJ = \Delta u(\varphi STJ)$$
$$\Delta u = u_{100-400\,hPa} - u_{850\,hPa}$$

Zonal Wind, Streamfunction



Circulation Metrics

Hadley Cell (HC)

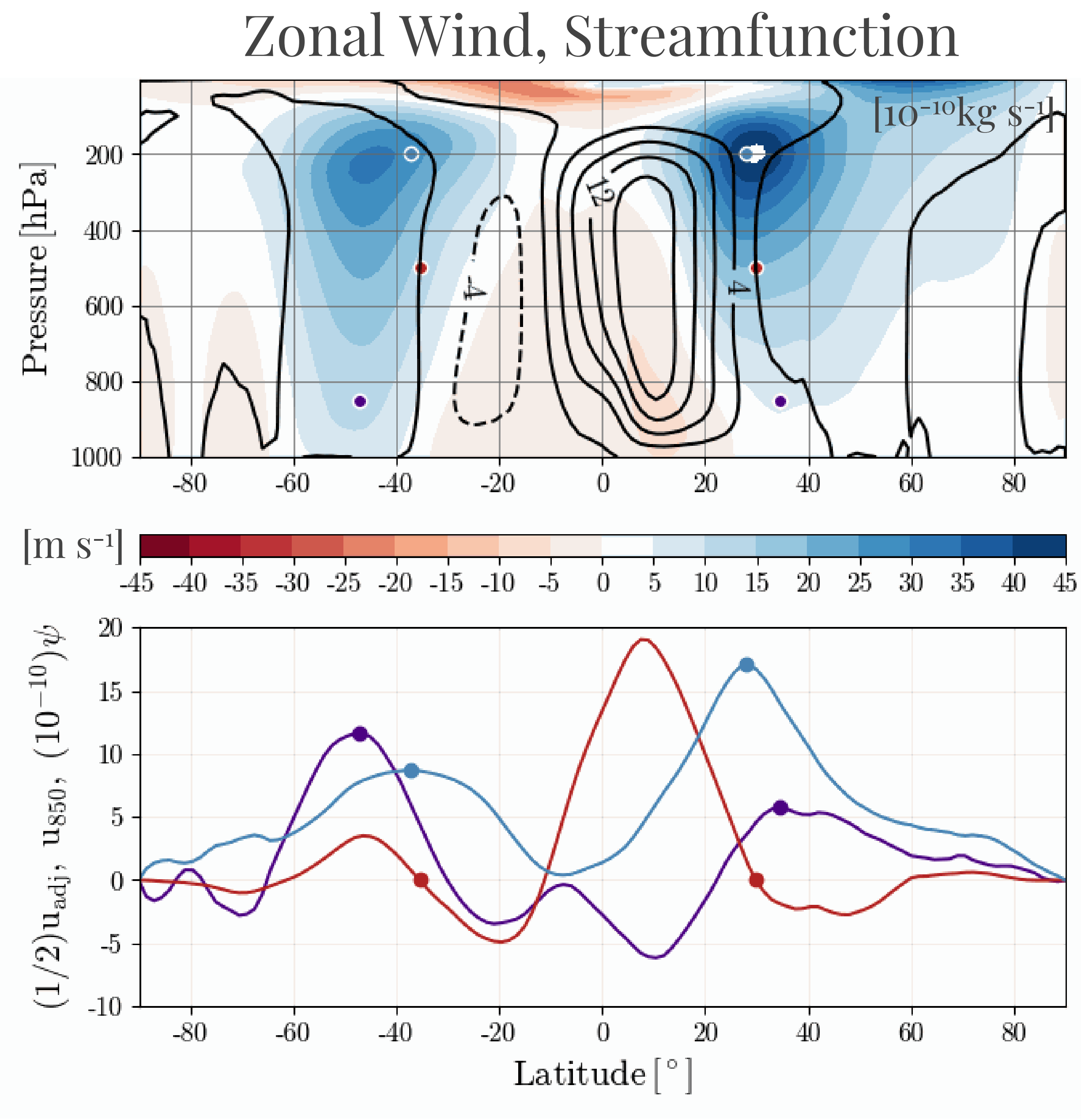
- (red) "PSI500"
  $\varphi HC = \varphi(\psi_{500\,hPa} = 0)$

Eddy-Driven Jet (EDJ)

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

Subtropical Jet (STJ)

- (blue) $\varphi STJ = \varphi(max(\Delta u))$
  $uSTJ = \Delta u(\varphi STJ)$
  $\Delta u = u_{100-400\,hPa} - u_{850\,hPa}$



Metric Relationships

CMIP5

Coupled Model Intercomparison Project (Phase 5)

Output from coupled simulations

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

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Output from coupled simulations

piControl

Control with pre-industrial levels of CO_2

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GISS-E2-H	

CMIP5

Coupled Model Intercomparison Project (Phase 5)

Output from coupled simulations

piControl

Control with pre-industrial levels of CO_2

abrupt4xCO2

Abrupt quadrupling of CO_2, 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
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GISS-E2-H	

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)

Menzel et al. 2019

CMIP5: Interannual

Southern Hemisphere

	ANN	DJF	MAM	JJA	SON
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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 / ϕEDJ	**0.52*** (0.1)	**0.47*** (0.11)	**0.48*** (0.11)	**0.4*** (0.11)	**0.45*** (0.08)

Menzel et al. 2019

CMIP5: Interannual

Southern Hemisphere

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ϕHC maxSTJ	**-0.19** (0.16)	**-0.34** (0.26)	**-0.14** (0.16)	**-0.25*** (0.13)	**-0.1** (0.17)
ϕHC ϕEDJ	**0.52*** (0.14)	**0.72*** (0.06)	**0.46*** (0.14)	**0.24** (0.17)	**0.4*** (0.21)

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ϕHC maxSTJ	**-0.39*** (0.14)	**-0.3*** (0.13)	**-0.52*** (0.13)	**-0.29*** (0.18)	**-0.15** (0.15)
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Menzel et al. 2019

CMIP5: Interannual

	Natural Variability
HC Location STJ Strength	—

More poleward Hadley cell, weaker subtropical jet

Northern Hemisphere

	DJF	MAM	JJA	SON
ϕHC / ϕSTJ	.02 (0.12)	0.29* (0.16)	0.2 (0.17)	-0.08 (0.09)
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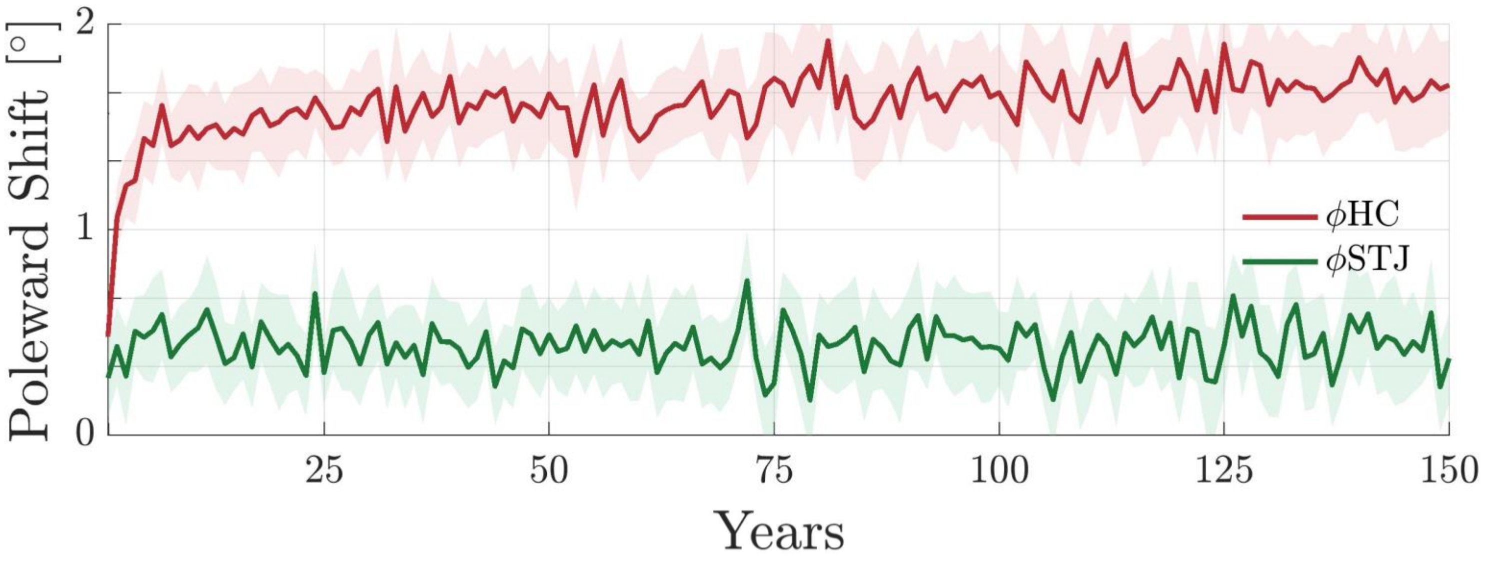
Menzel et al. 2019

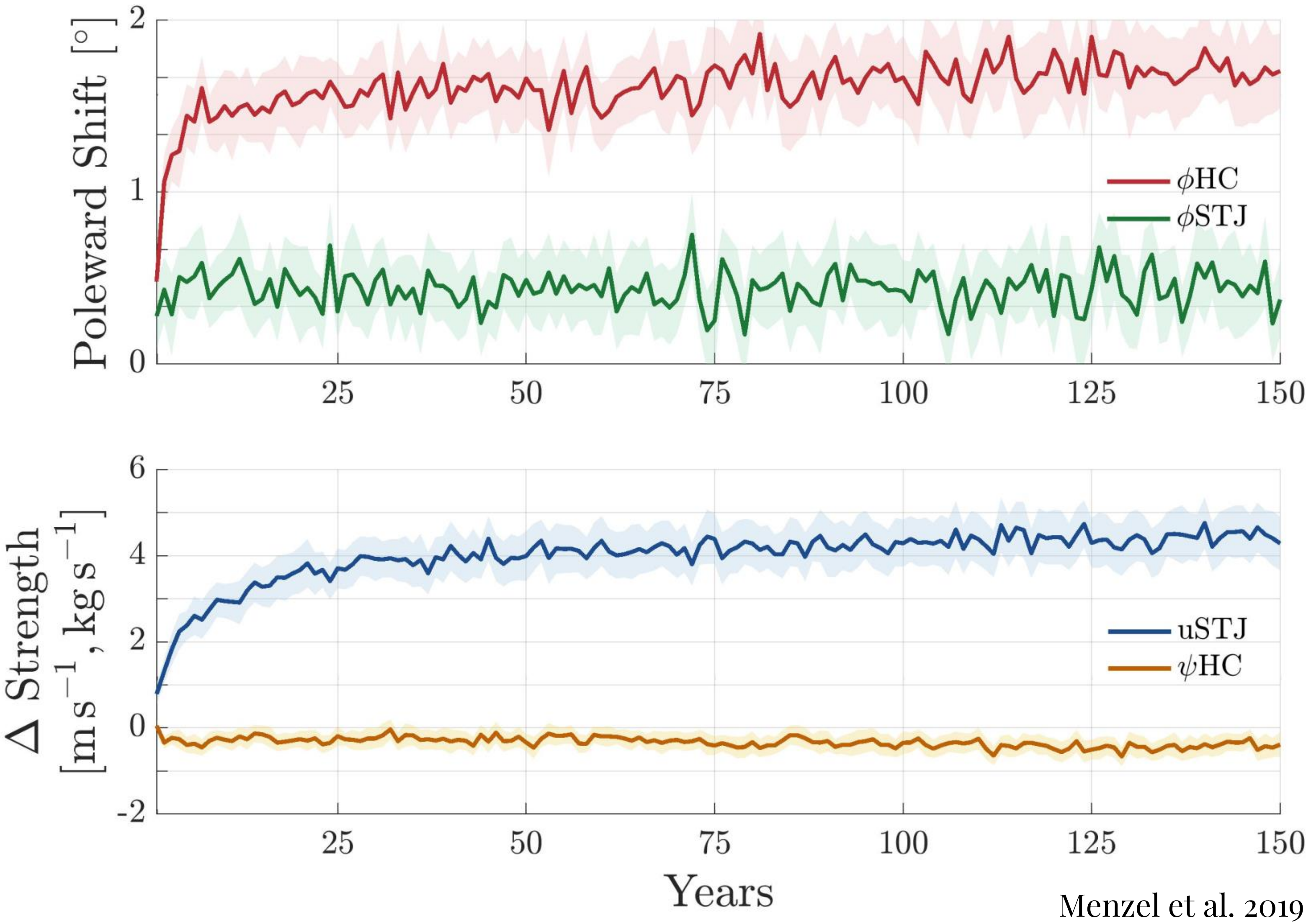
CMIP5: Transient Response



Menzel et al. 2019

Time series of metrics' response to $4xCO_2$

CMIP5: Transient Response



Menzel et al. 2019

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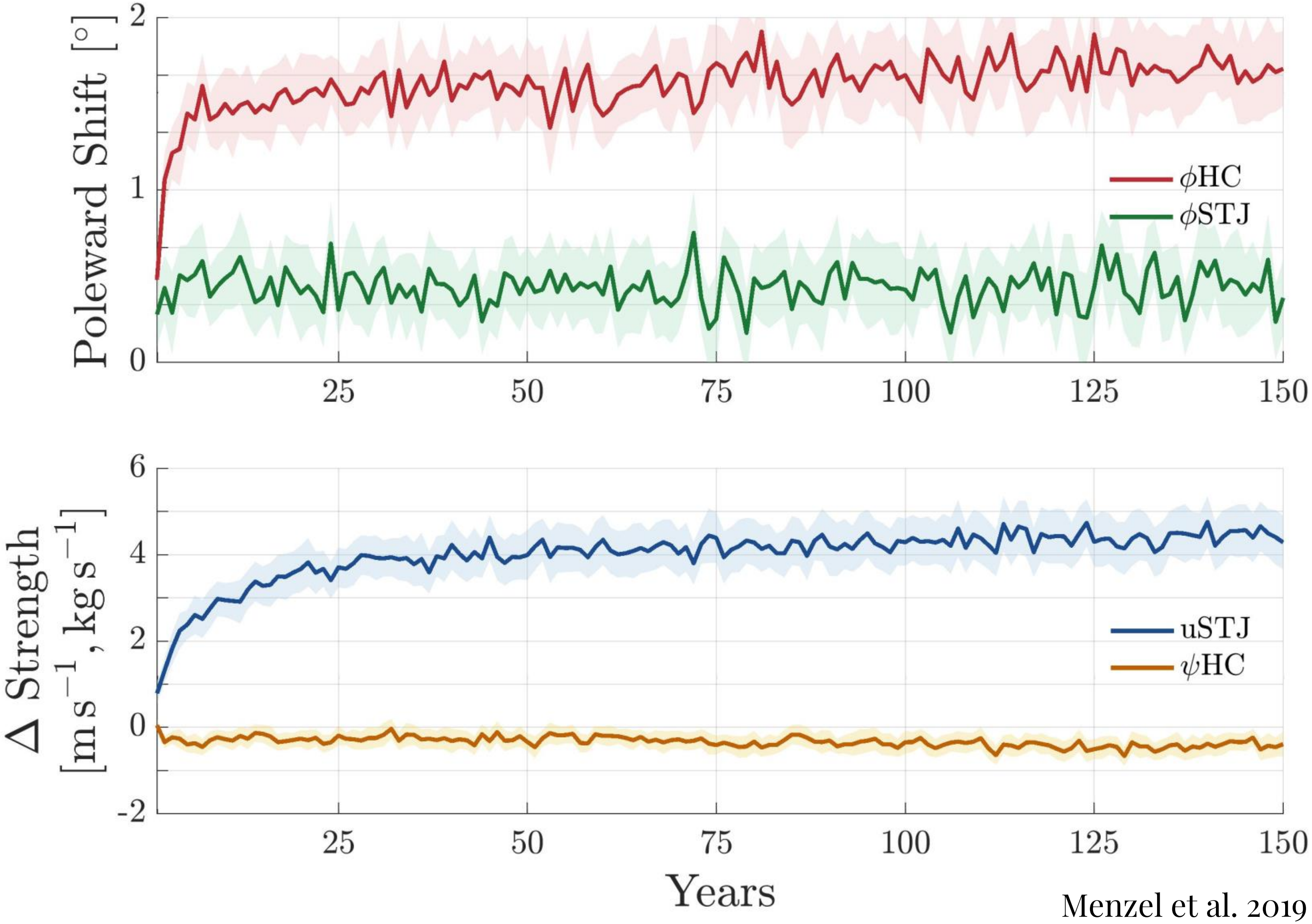


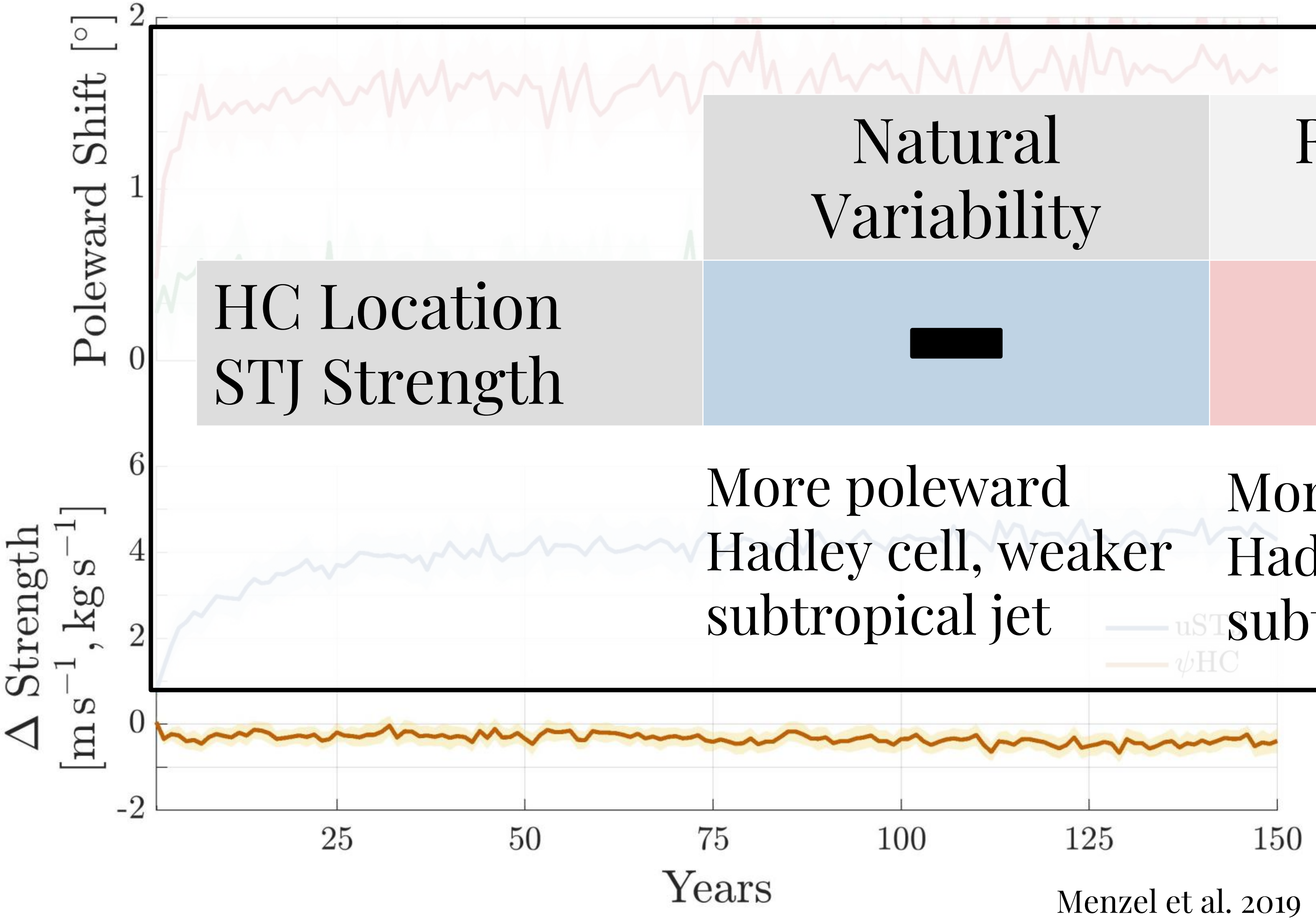
Menzel et al. 2019

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: Transient Response

	Natural Variability	Response to 4xCO2
HC Location STJ Strength	−	+
	More poleward Hadley cell, weaker subtropical jet	More poleward Hadley cell, stronger subtropical jet



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Menzel et al. 2019

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Conclusion:
The subtropical jet (STJ) is not coupled to the Hadley cell (HC), there must be physical processes responsible for their distinctive behavior.

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Menzel et al. 2019

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Menzel et al. 2019

Lingering Question:

What are the physical processes responsible for the distinct behavior of the HC and STJ?

Physical Balances

Meridional Flow Balance

$$(f + \vec{\zeta})\bar{v} = \frac{\partial}{\partial y}(\overline{u'v'})$$

Coriolis parameter

relative vorticity

mean meridional flow

eddy momentum flux

Meridional Flow Balance

$$\left(f + \vec{\zeta}\right)\bar{v} = \frac{\partial}{\partial y}\left(\overline{u'v'}\right)$$

Coriolis parameter

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eddy momentum flux

If eddies are negligible...

$$\left(f + \vec{\zeta}\right)\bar{v} = 0$$

Meridional flow is angular-momentum conserving!

Meridional Flow Balance

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If not...

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Meridional flow is set by eddies!

Meridional Flow Balance

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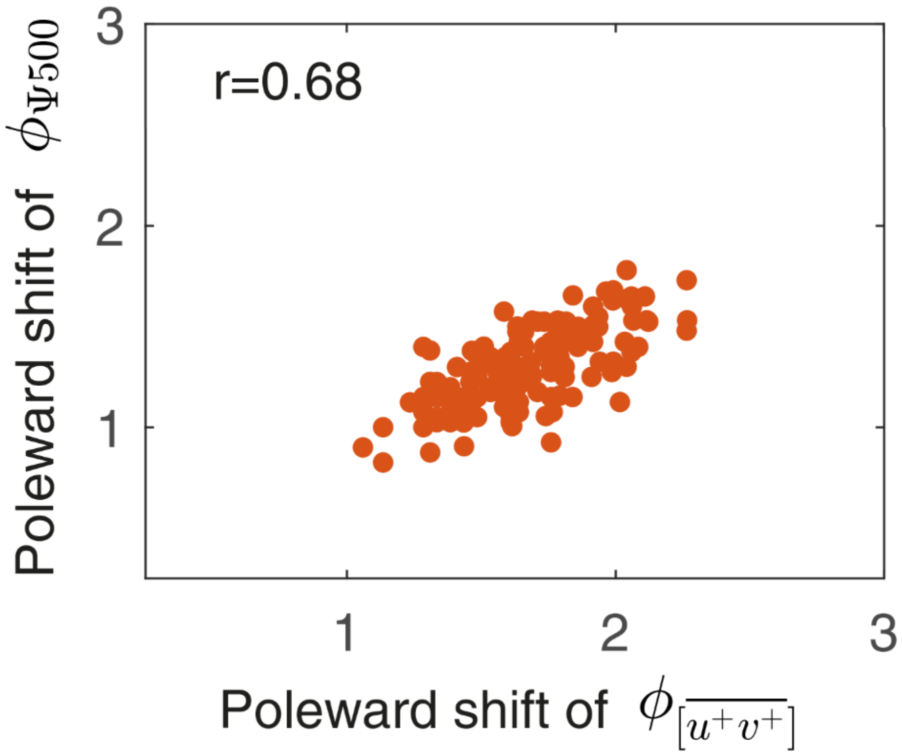

Chemke & Polvani 2019

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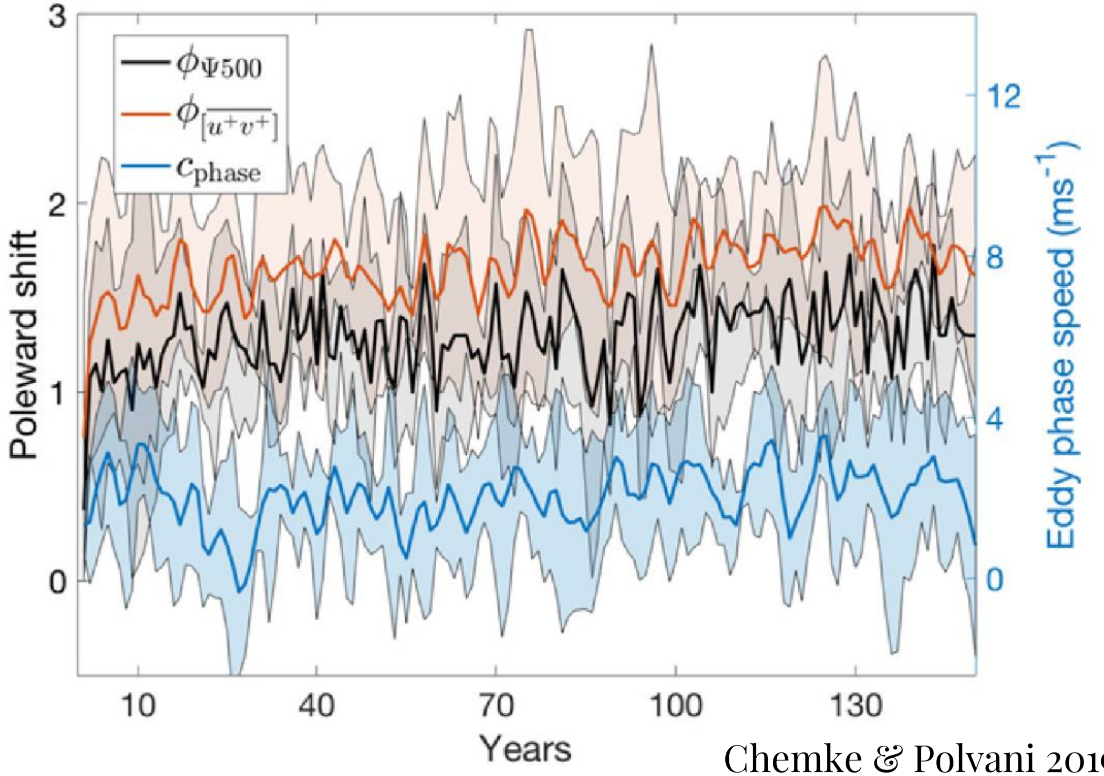

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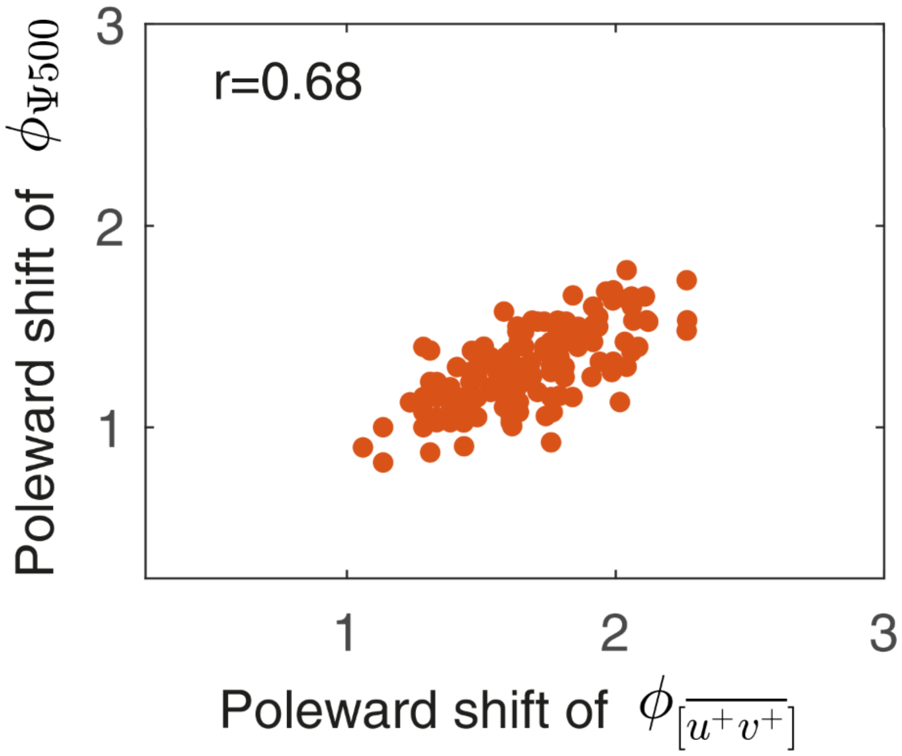


Chemke & Polvani 2019

Meridional flow is set by eddies!

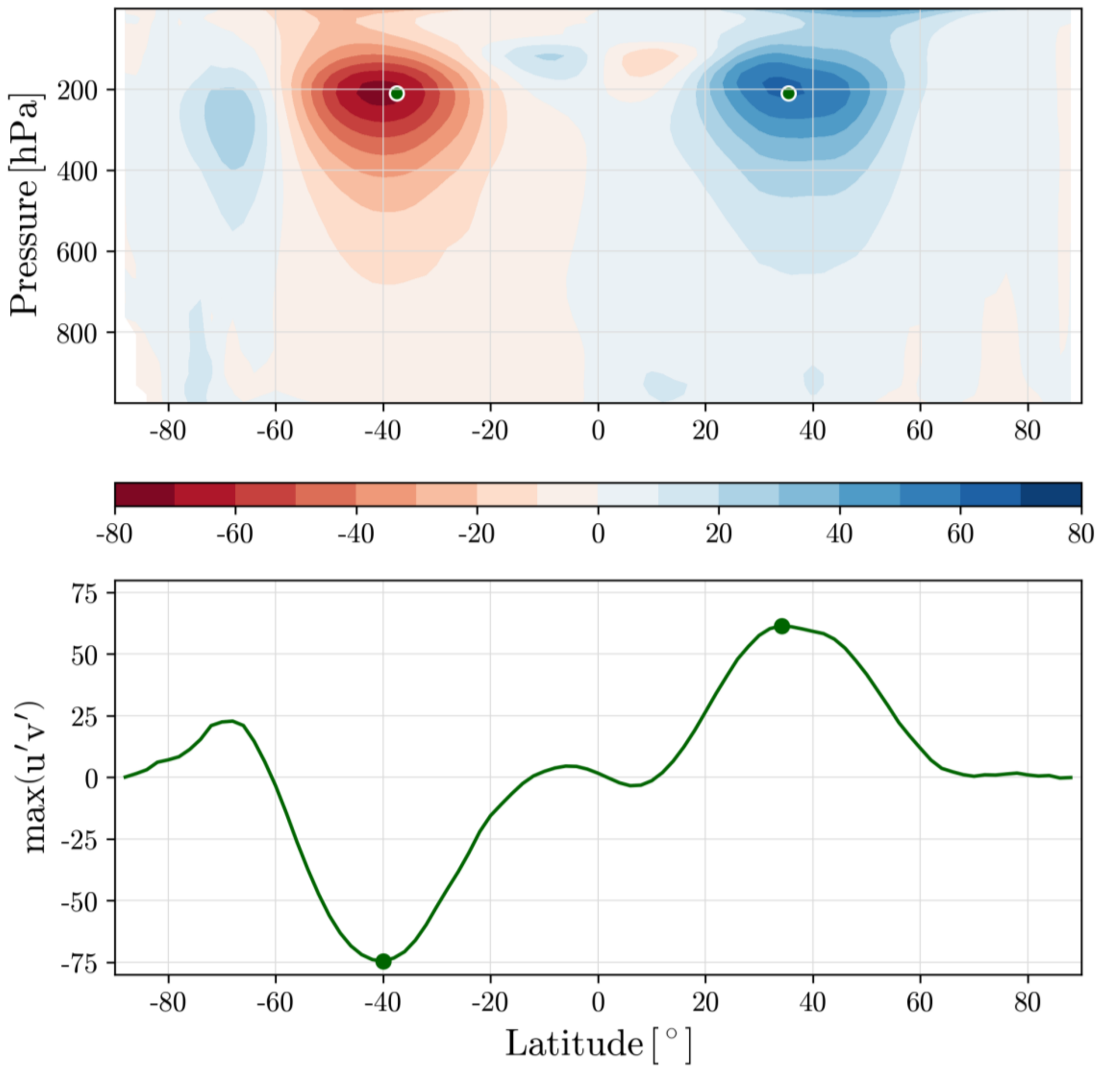
Meridional Flow Balance

$$(f+\vec{\zeta})\bar{v}=\frac{\partial}{\partial y}\left(\overline{u'v'}\right)$$

Maximum Eddy Momentum Flux

- $\varphi(\overline{u'v'})=\varphi\left(max(\overline{u'v'})\right)$

Eddy Momentum Flux



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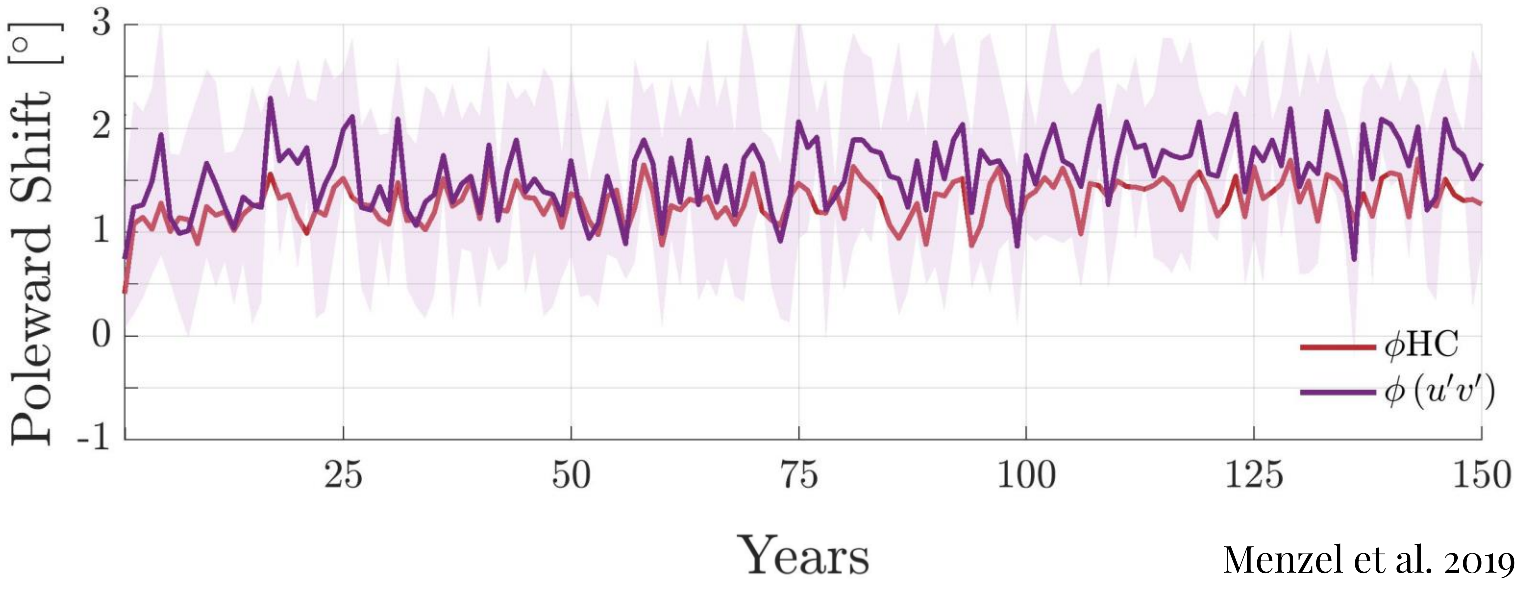

Menzel et al. 2019

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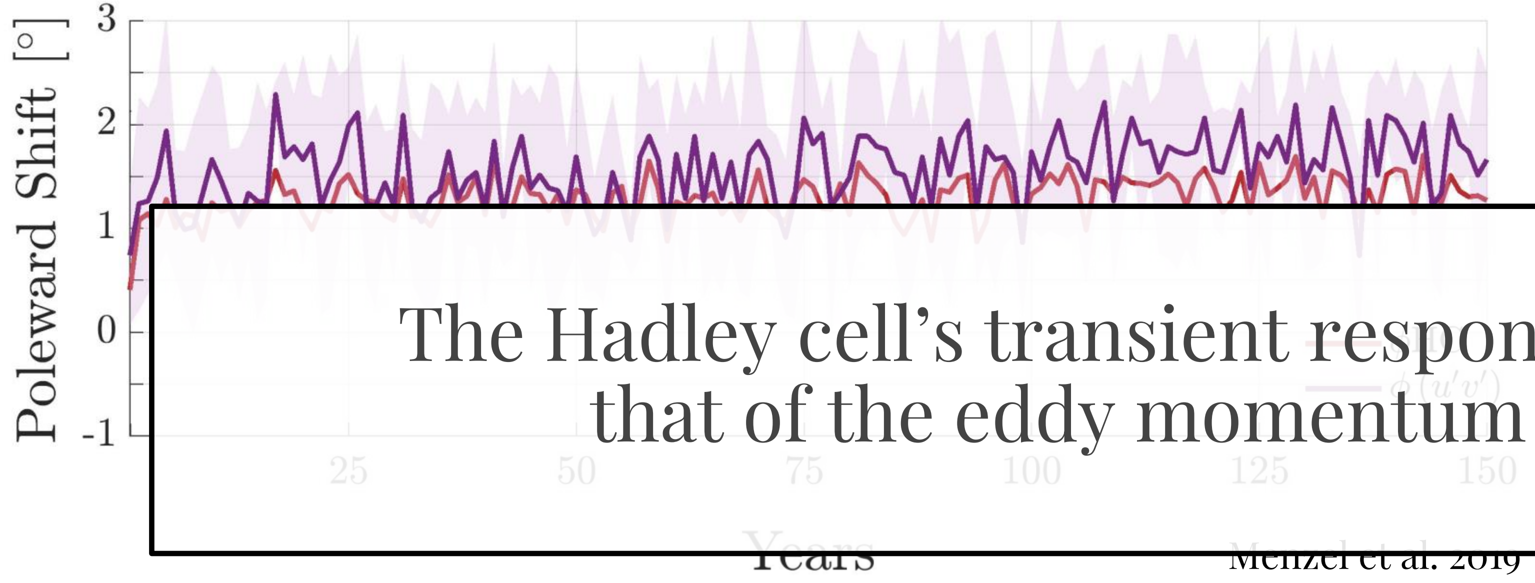
$\varphi(u'v')$	poleward	5

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

Meridional Flow Balance



Menzel et al. 2019

	Shift/Change	τ
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HC edge:

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

The Hadley cell's transient response follows that of the eddy momentum flux

Subtropical Static Stability

Connection between Hadley cell and subtropical static stability

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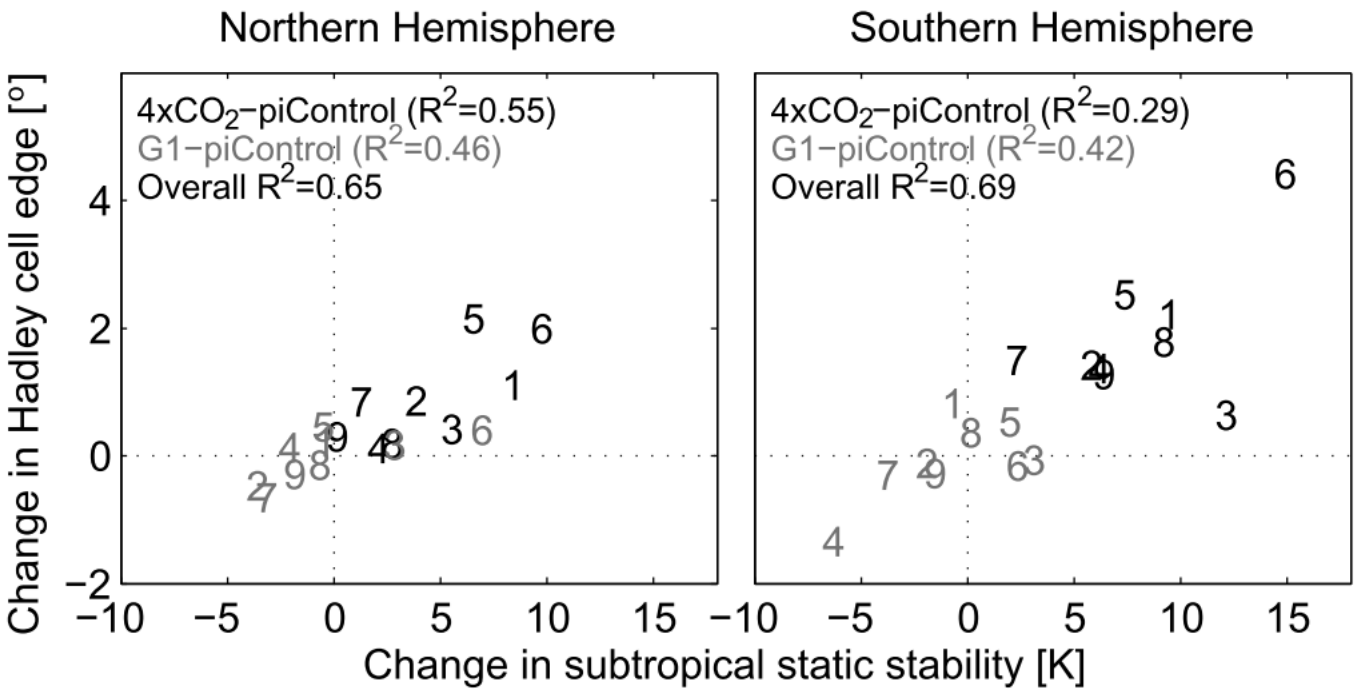
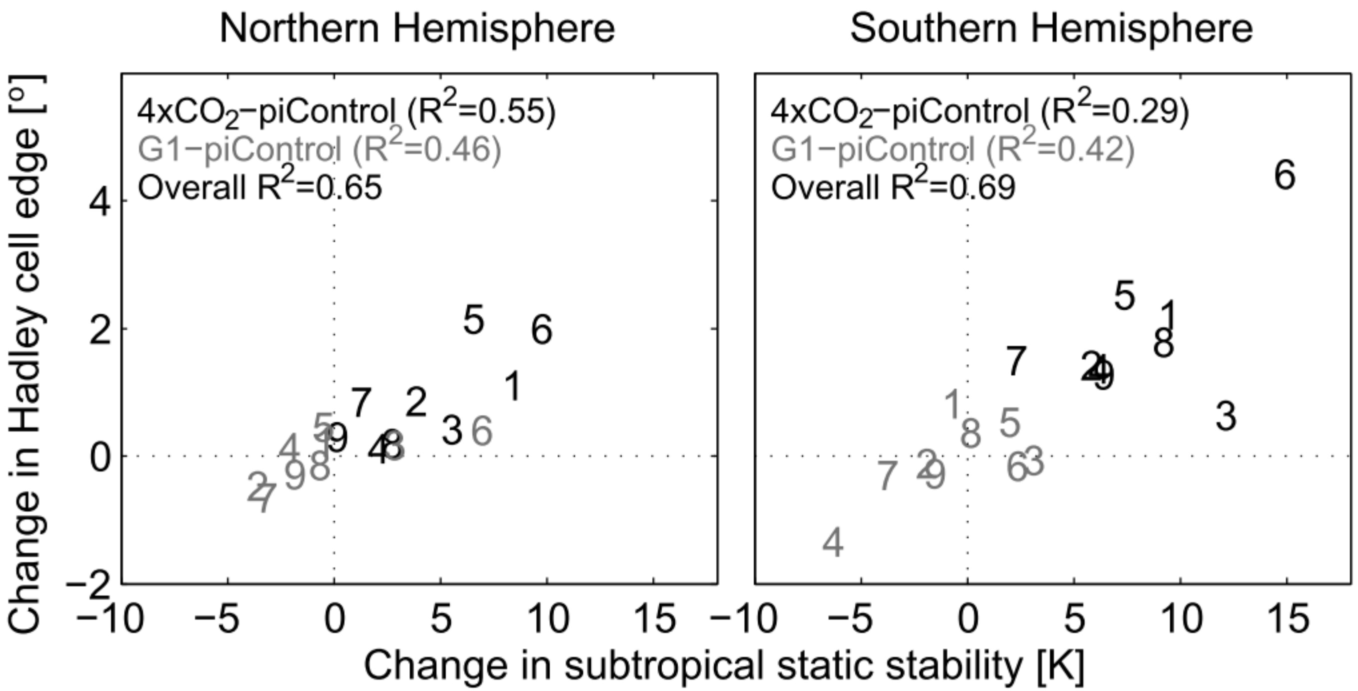


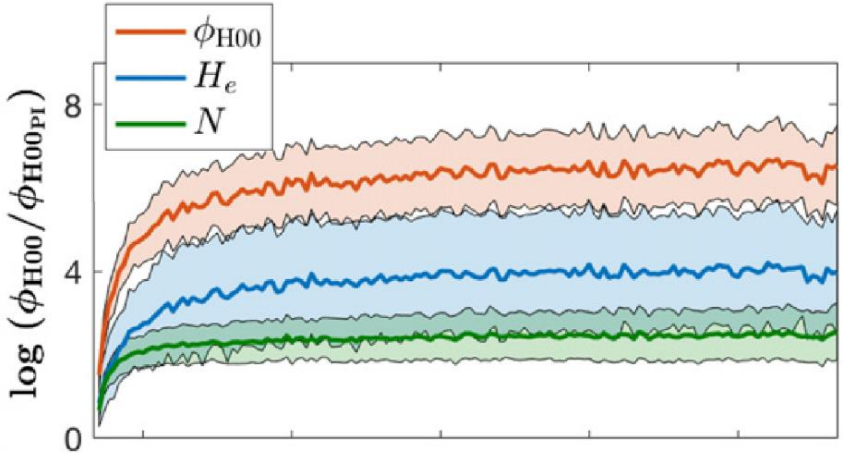
Davis et al. 2016

Subtropical Static Stability

Connection between Hadley cell and subtropical static stability



Davis et al. 2016



Chemke & Polvani 2019

Thermal Wind Balance

$$\frac{\partial \bar{u}}{\partial p} = \frac{1}{f}\frac{\partial}{\partial y}\left(\frac{-R\bar{T}}{p}\right)$$

vertical gradient of zonal wind

meridional temperature gradients

Thermal Wind Balance

$$\frac{\partial \bar{u}}{\partial p} = \frac{1}{f}\frac{\partial}{\partial y}\left(\frac{-R\bar{T}}{p}\right)$$

vertical gradient of zonal wind

meridional temperature gradients

$$\frac{\partial \bar{u}}{\partial p} \propto \frac{\partial T}{\partial y}$$

Upper level winds proportional to temperature gradients!

Thermal Wind Balance

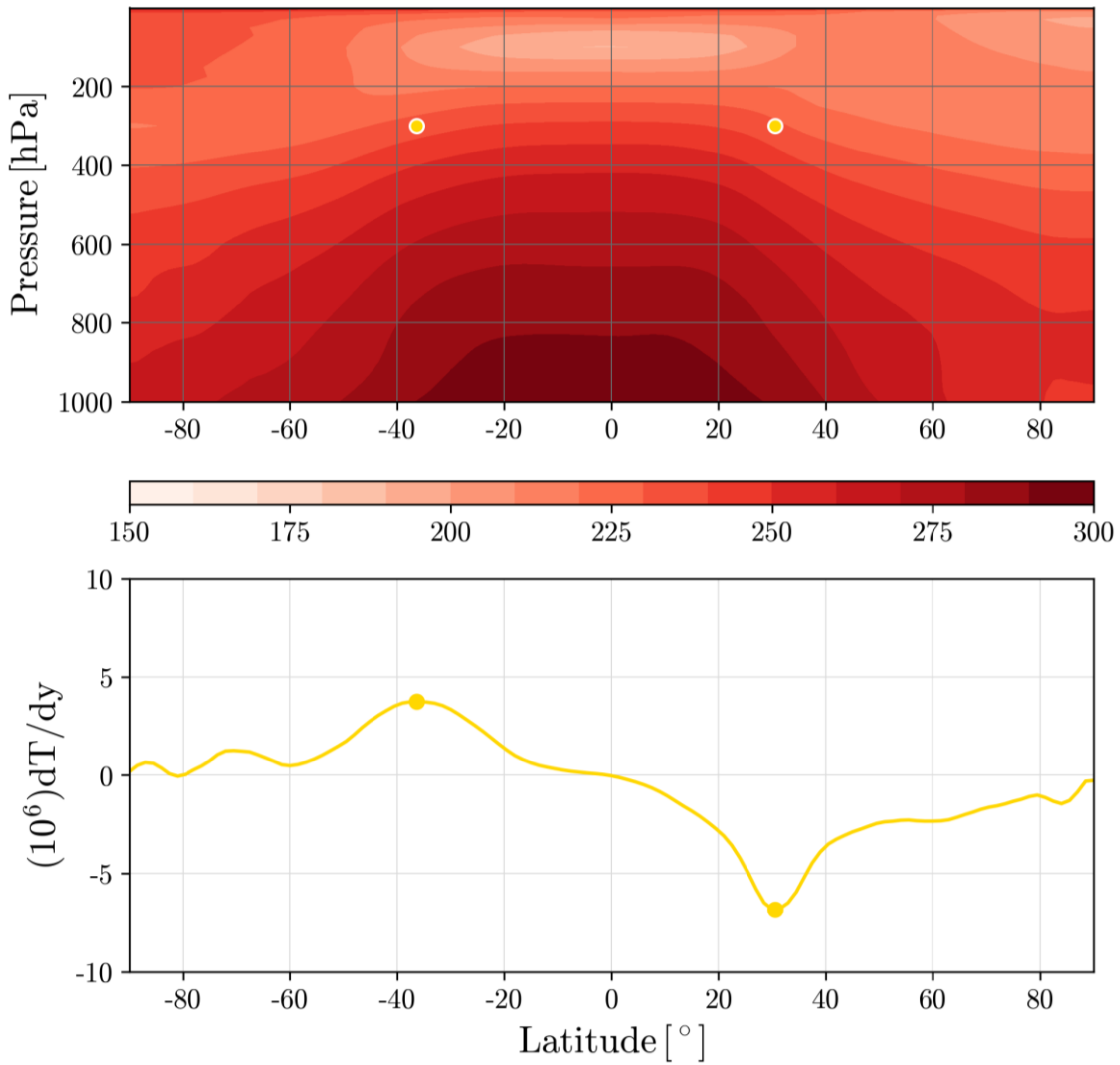
$$\frac{\partial \bar{u}}{\partial p} = \frac{1}{f}\frac{\partial}{\partial y}\left(\frac{-R\bar{T}}{p}\right)$$

Meridional Temperature Gradients

- $$\varphi\frac{\partial T}{\partial y} = \varphi\left(max\left(\frac{\partial T}{\partial y}\right)_{200-400\ hPa}\right)$$

$$max\frac{\partial T}{\partial y} = max\left(\frac{\partial T}{\partial y}\right)_{200-400\ hPa}$$

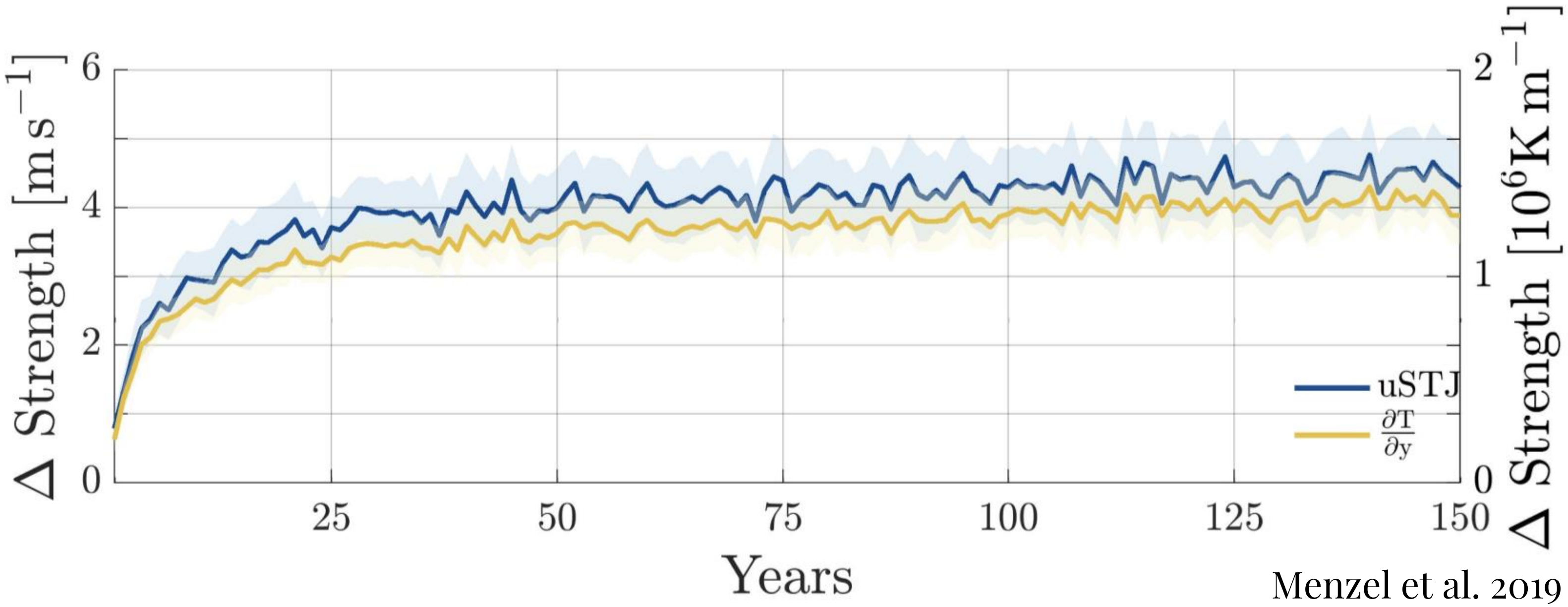
Meridional Temperature Gradient



Thermal Wind Balance

	Shift/Change	τ
$uSTJ$	strengthening	40
$\partial T/\partial y$	strengthening	40

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



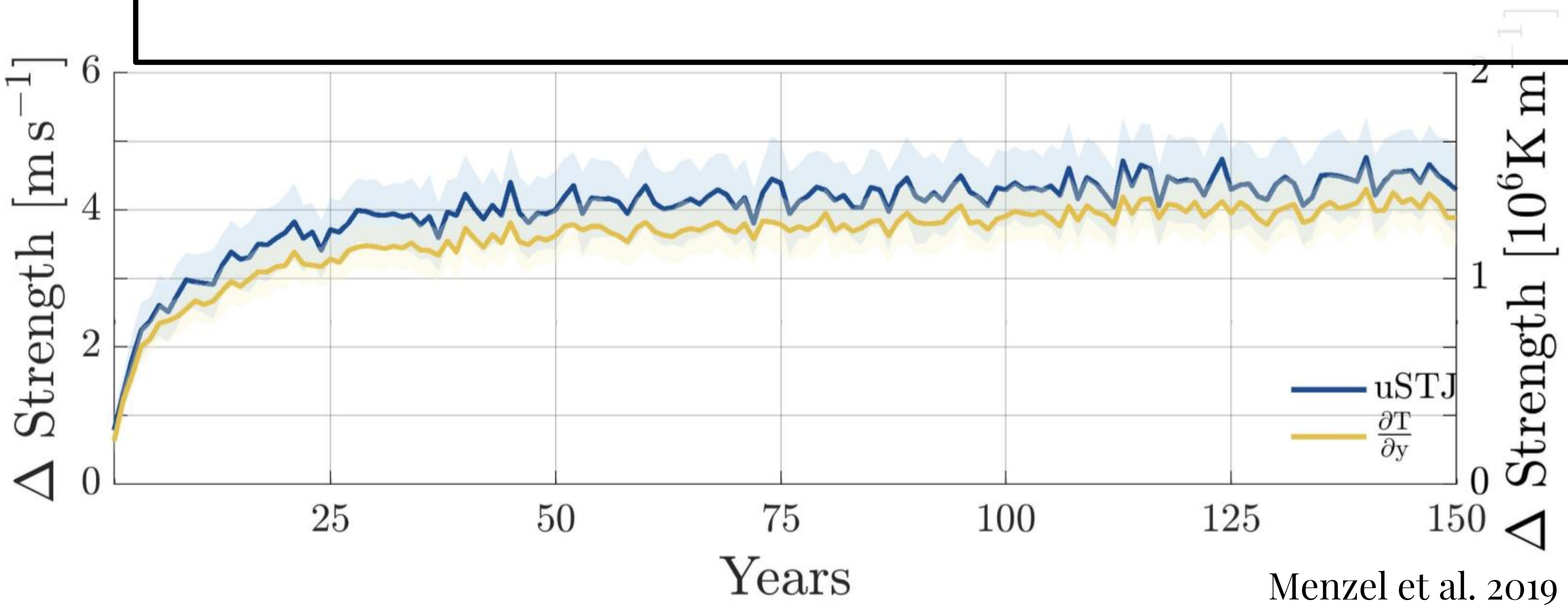
Menzel et al. 2019

Thermal Wind Balance

	Shift/Change	τ
uSTJ	strengthening	40
$\partial T/\partial y$	strengthening	40

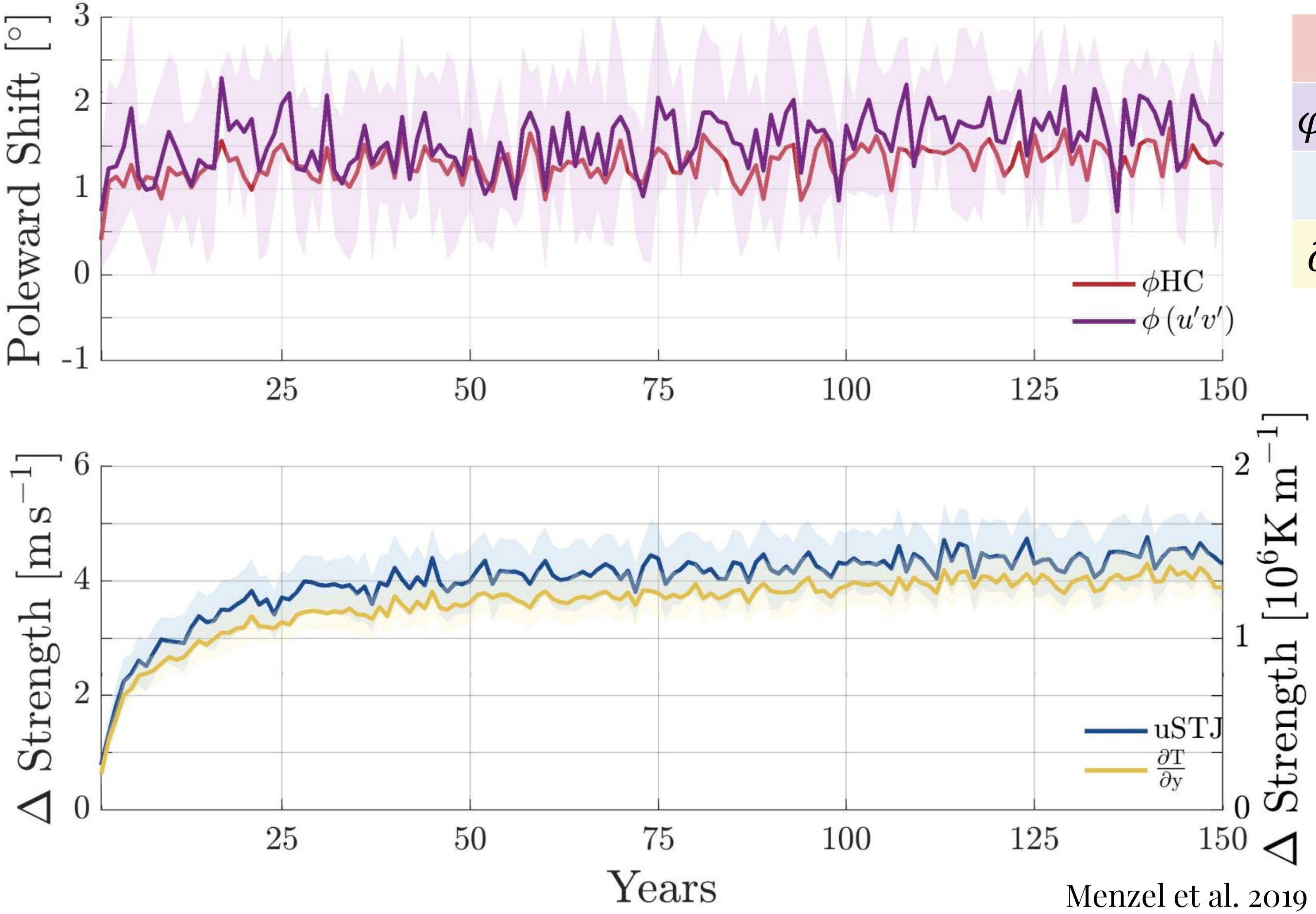
The subtropic jet's transient response follows that of the meridional temperature gradients

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



Menzel et al. 2019

Physical Balances



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 $\varphi(u'v')$

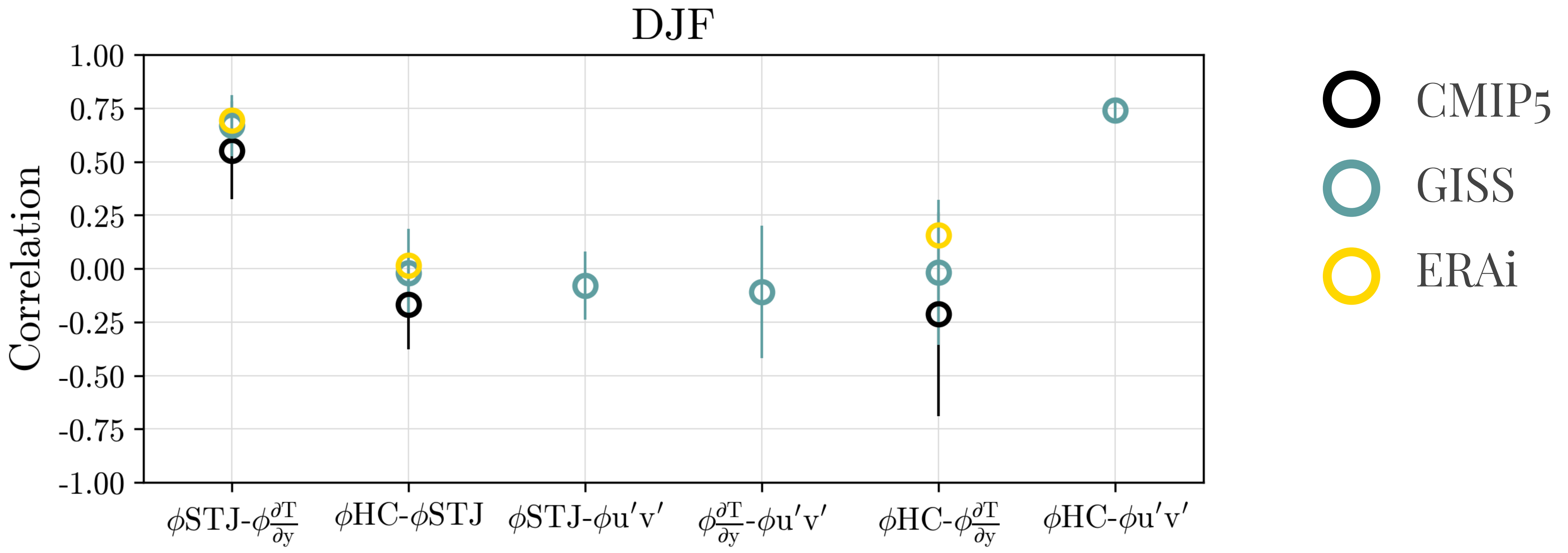
STJ strength:
- max meridional temperature gradient $\partial T/\partial y$

Physical Balances

GISS-E2.1: NASA Goddard Institute for Space Studies' Global Climate Model

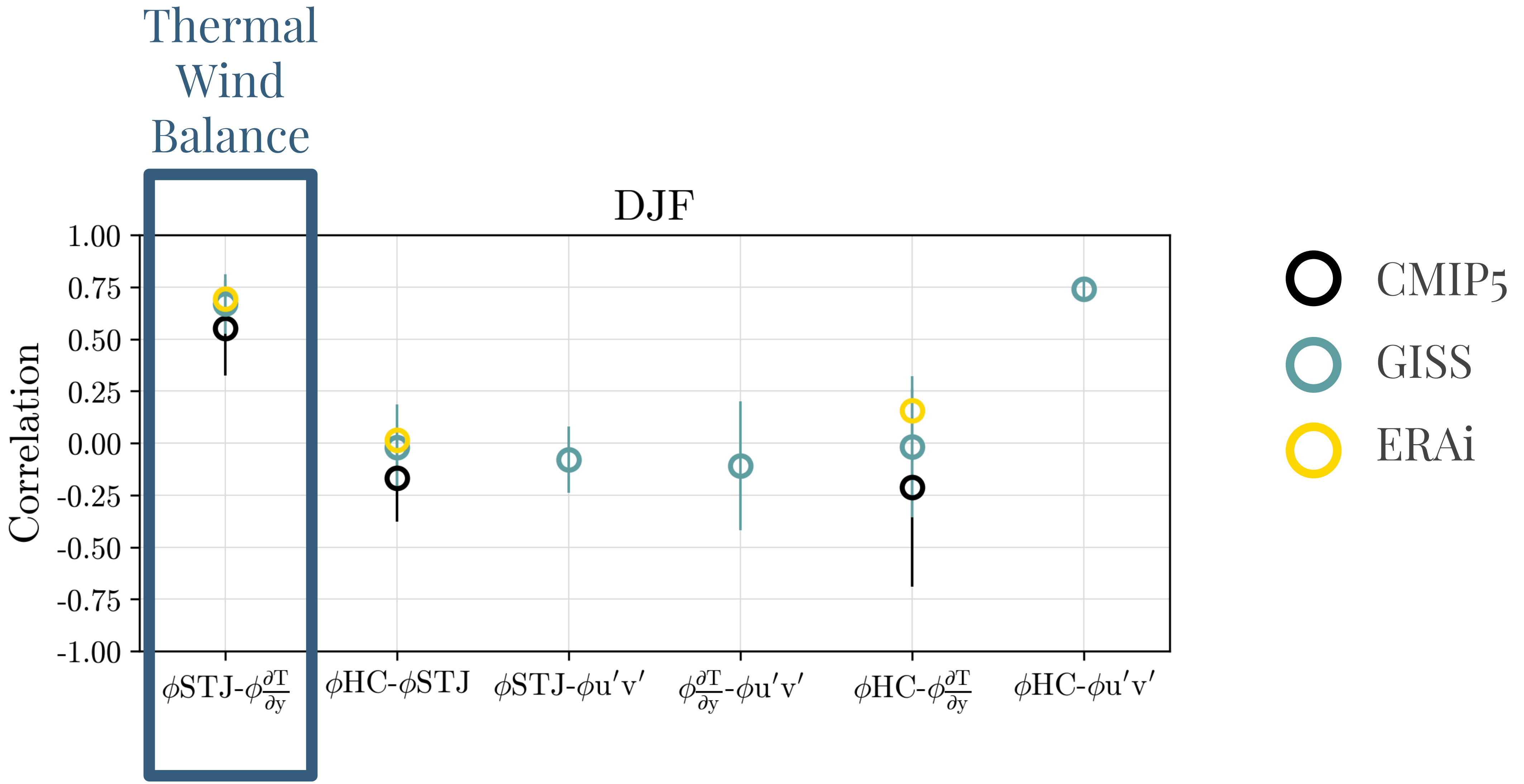
10 simulations, abrupt $NxCO_2$

ERAi: ERA-interim reanalysis

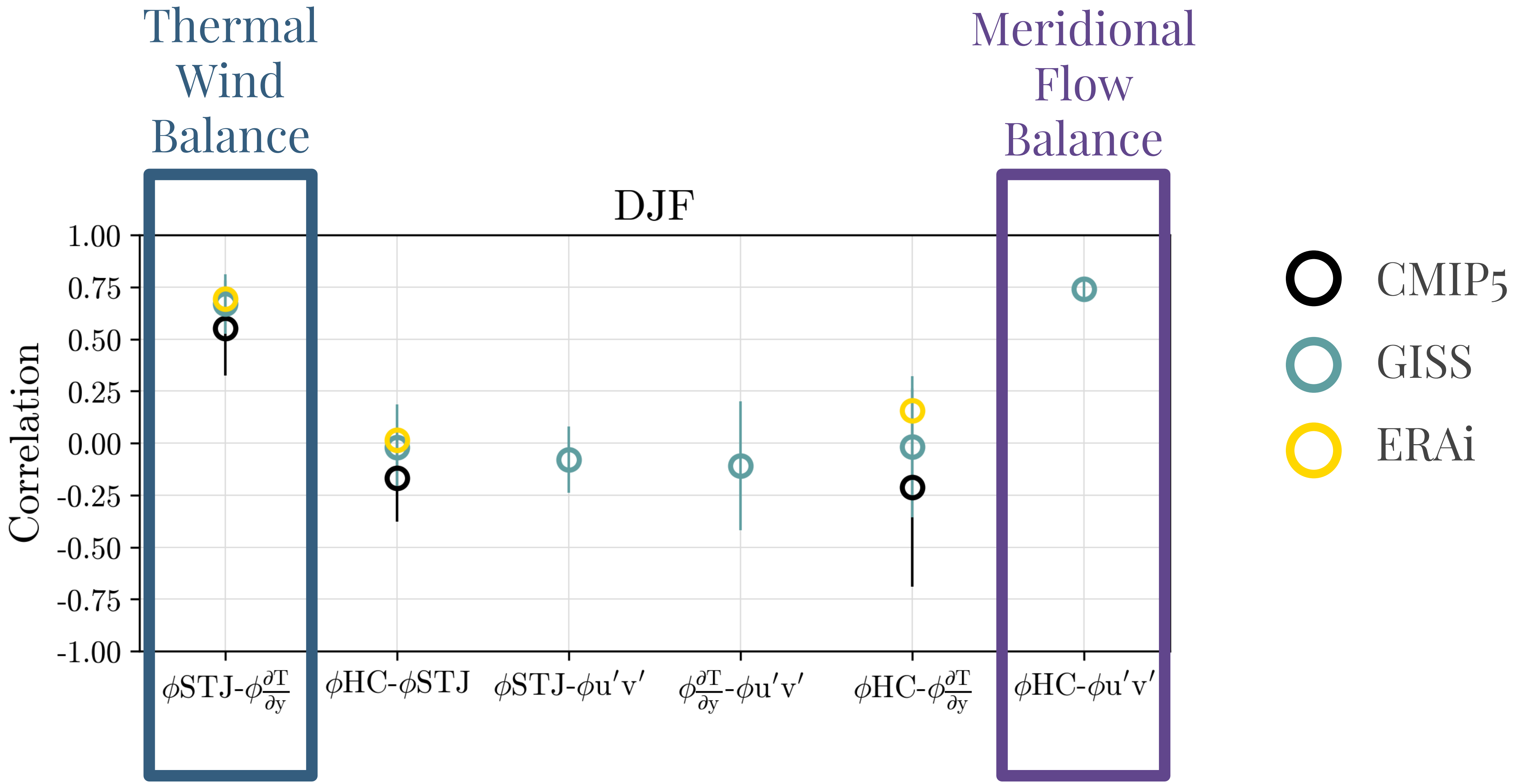


GISS output provided by Clara Orbe and Ivan Mitevski

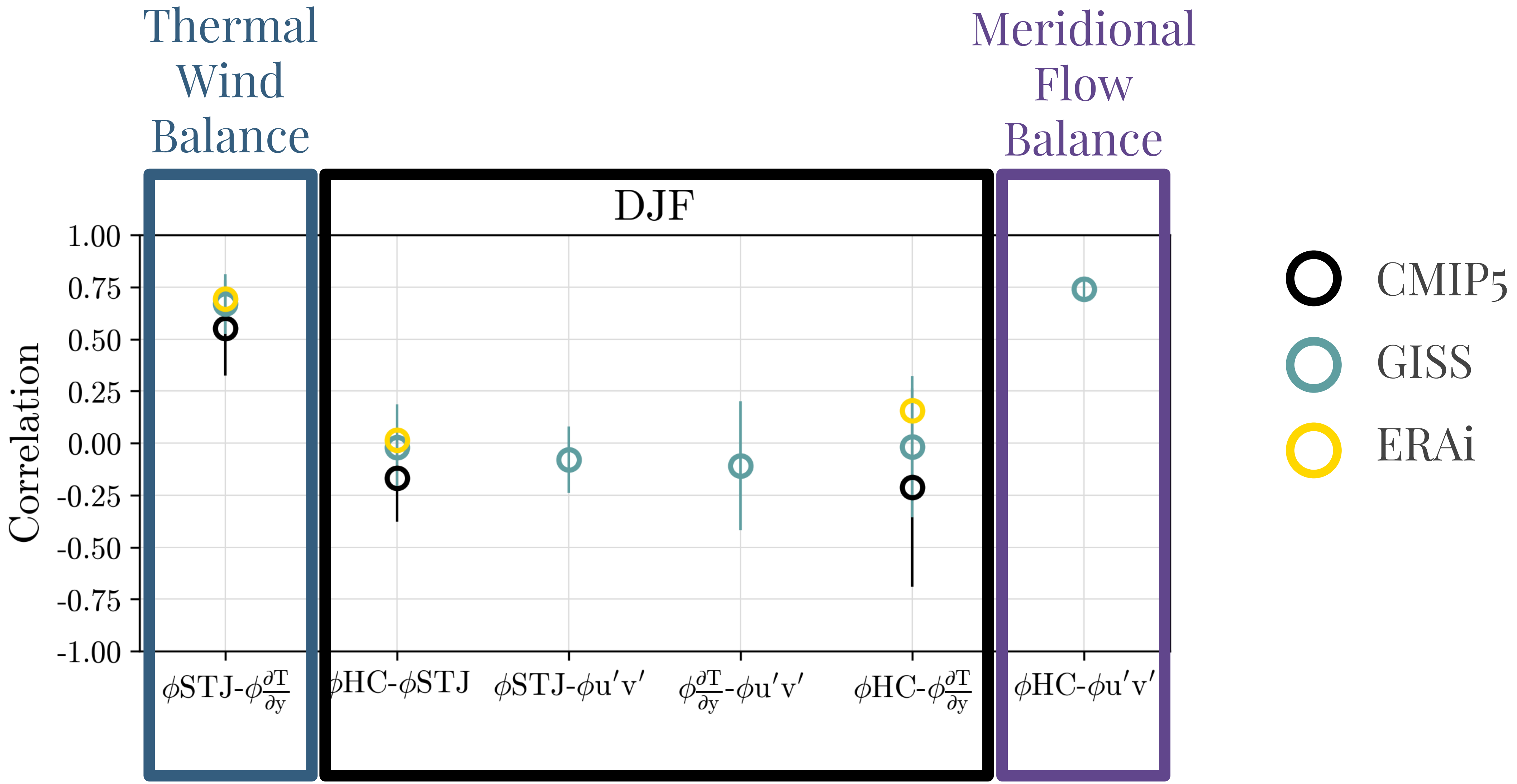
Physical Balances



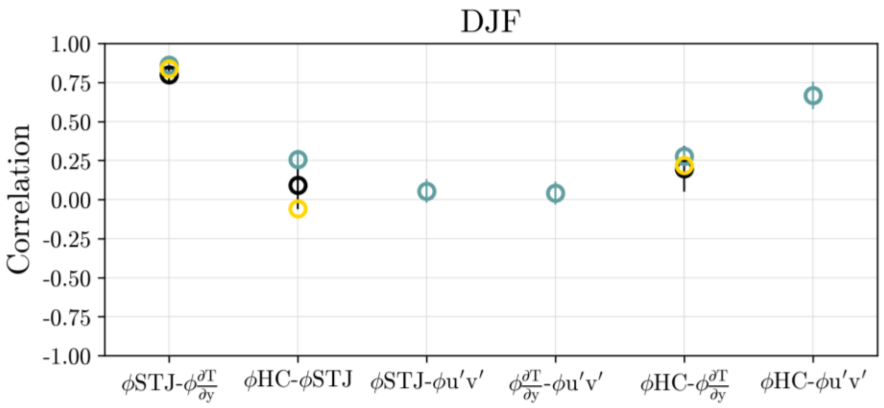
Physical Balances

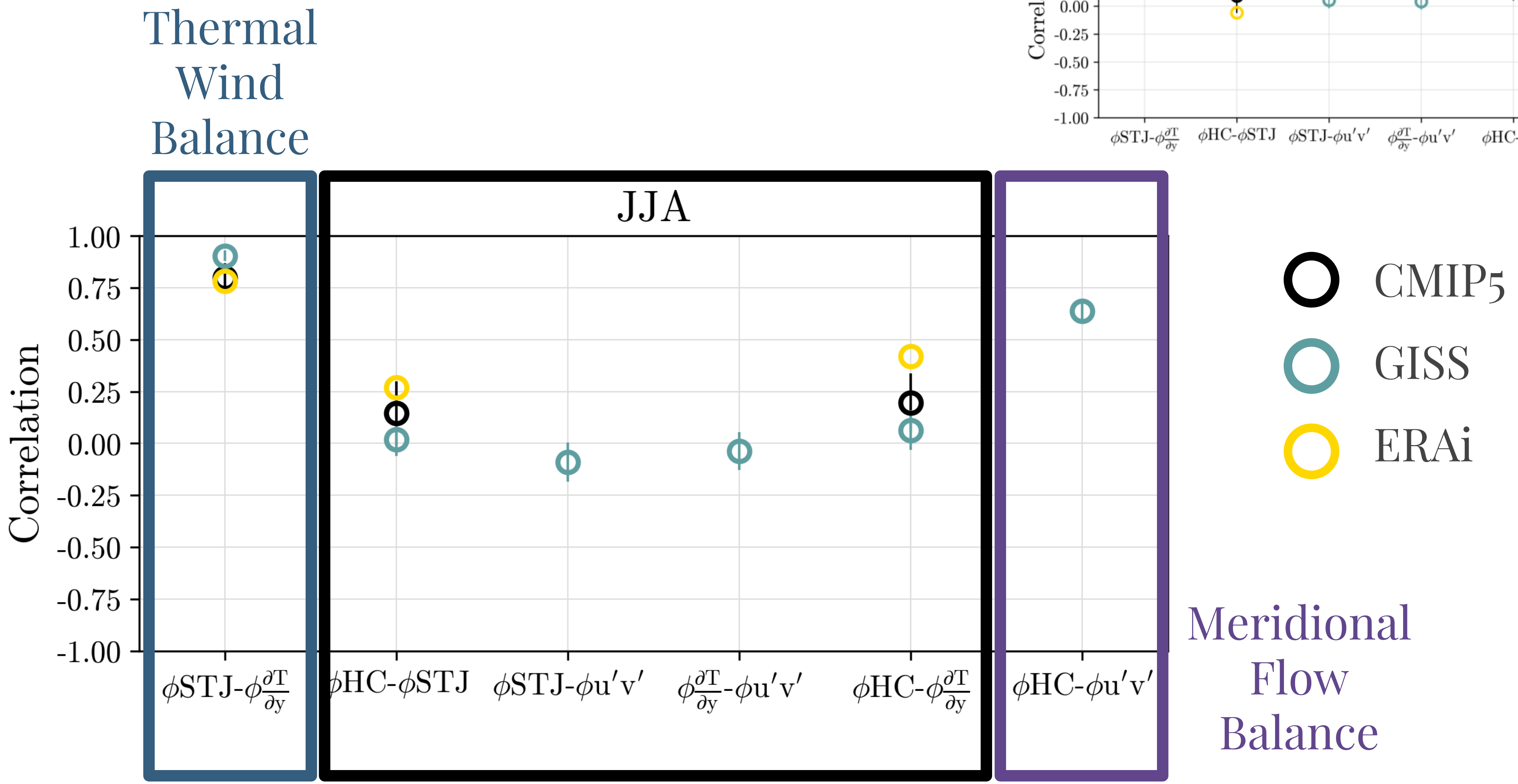


Physical Balances

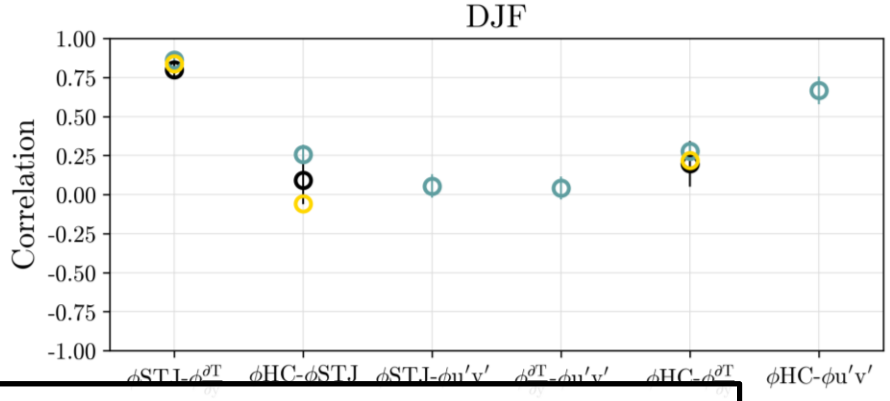


Physical Balances

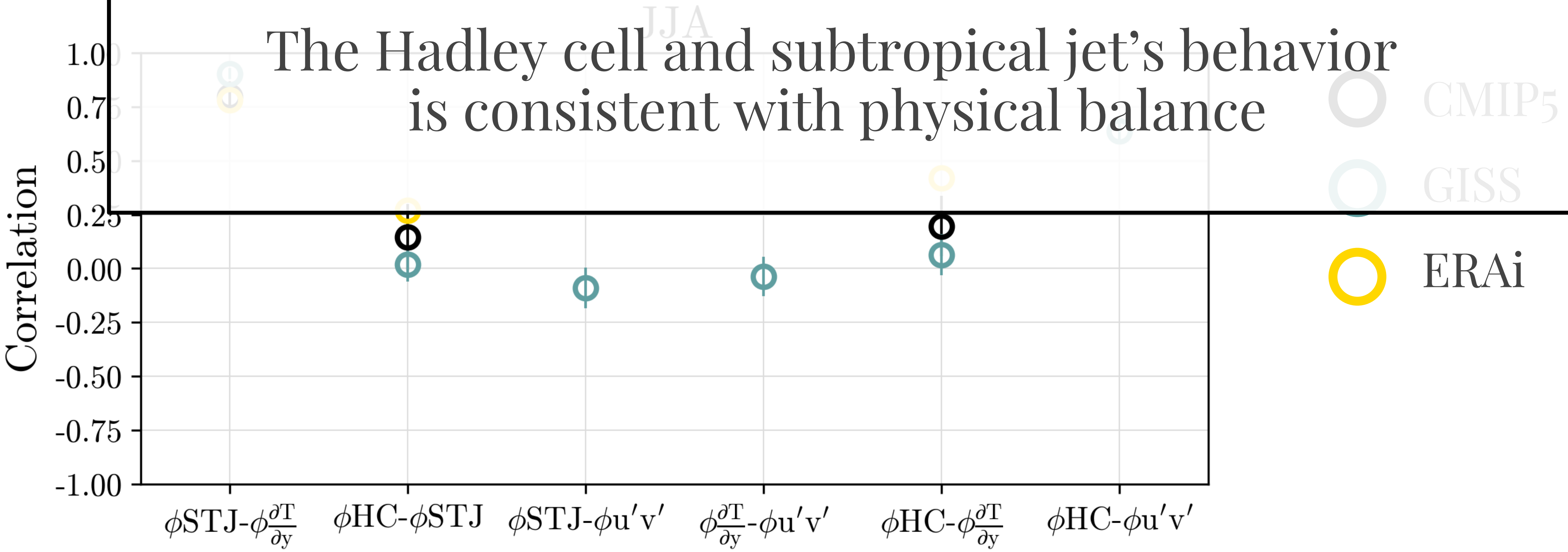




Physical Balances

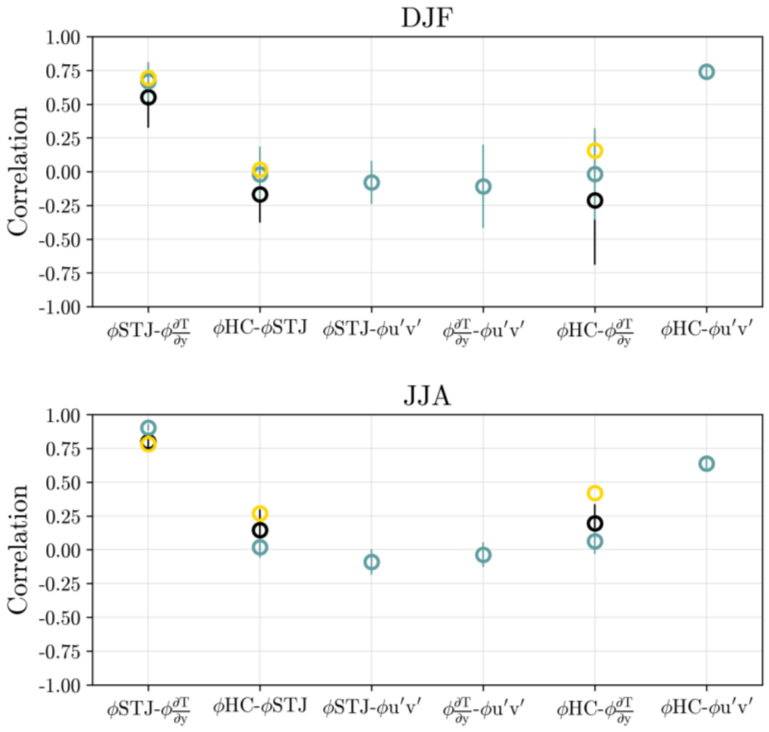


The Hadley cell and subtropical jet's behavior is consistent with physical balance

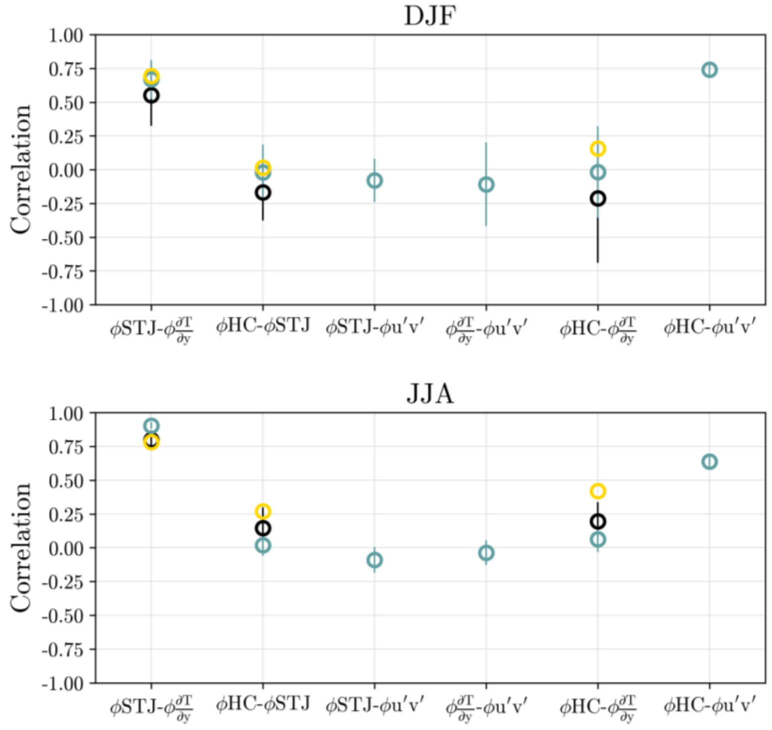


Physical Balances Analysis

Conclusion:
The Hadley cell (HC)'s behavior is consistent with <u>meridional flow balance</u> and subtropical jet (STJ)'s behavior is consistent with <u>thermal wind balance</u>



Physical Balances Analysis



Conclusion:
The Hadley cell (HC)'s behavior is consistent with meridional flow balance and subtropical jet (STJ)'s behavior is consistent with thermal wind balance

Lingering Question:

What model processes are necessary to replicate the STJ-HC relationship shown in comprehensive climate models?

Idealized Modelling

Model Hierarchy

decreasing complexity →

Hierarchy of Processes

Large-Scale Atmospheric Circulation	Earth System Models	Atmospheric GCMs	Aquaplanet Simulations	Dry Dynamical Core
Dynamics	Primitive equations	Primitive equations	Primitive equations	Primitive equations
Forcing	Atmospheric composition	Atmospheric composition	Solar heating, atmospheric composition	Equilibrium temperature
Boundary conditions	Dynamical ocean, sea-ice, land models	Prescribed SSTs	Ocean mixed layer, "slab ocean"	
Diabatic processes	Moist processes	Moist processes	Gray radiation, simplified convection scheme	

informed by Maher et al. 2019

Model Hierarchy

decreasing complexity →

Hierarchy of Processes

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Model Hierarchy

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informed by Maher et al. 2019

Model Hierarchy

decreasing complexity

Hierarchy of Processes

Does a decoupling of the Hadley cell (HC) and subtropical jet (STJ) occur in a fully dry atmospheric model?

Large-Scale Atmospheric Circulation	Earth System Models	Atmospheric GCMs	Aquaplanet Simulations	Dry Dynamical Core
Dynamics	Primitive equations	Primitive equations	Primitive equations	Primitive equations
Forcing	Atmospheric composition	Atmospheric composition	Solar heating, atmospheric composition	Equilibrium temperature
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Diabatic processes	Moist processes	Moist processes	Gray radiation, simplified convection scheme	

informed by Maher et al. 2019

Dry Dynamical Core Models

Forced by an equilibrium temperature profile

$$\frac{\partial T}{\partial t} = \frac{T - T_{eq}}{\tau}$$

Classical Setup: Held & Suarez (1994)

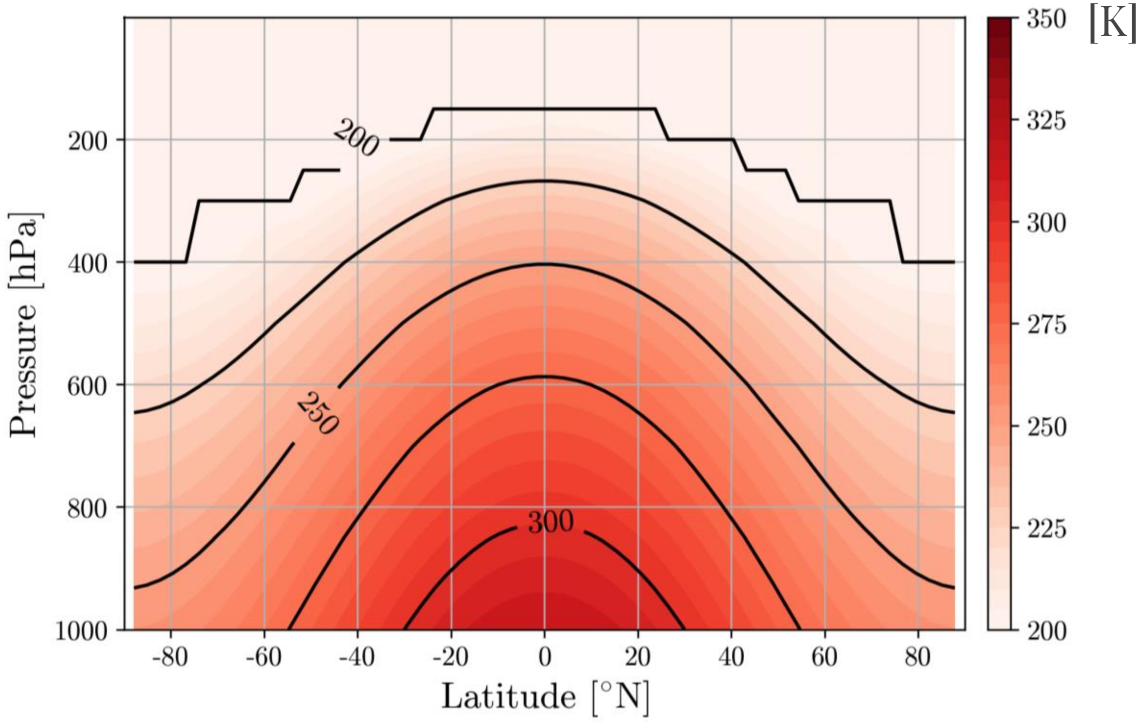
T_{eq} set by an analytical function

$$T_{eq} = max\left\{T_{strat}, \left[T_0 - \delta_y(\sin\phi)^2 + T' - \delta_z \log\left(\frac{p}{p_0}\right)(\cos\phi)^2\right]\left(\frac{p}{p_0}\right)^{\kappa}\right\}$$

Dry Dynamical Core Models

Held & Suarez (1994)

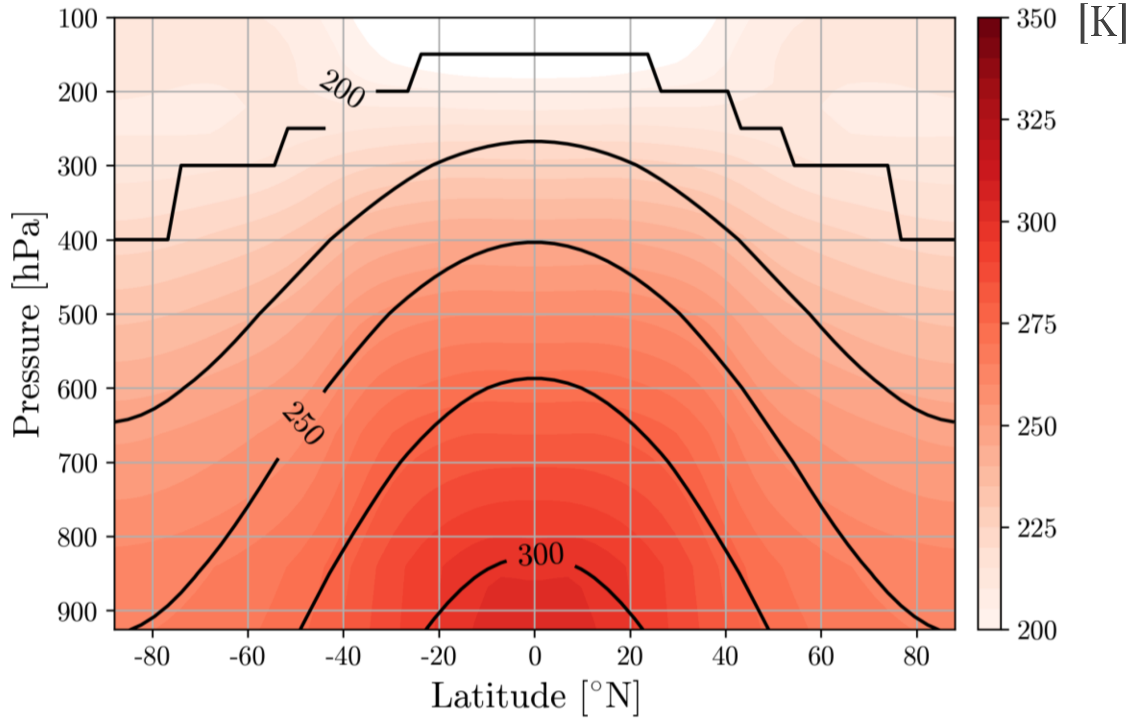
Equilibrium Temperature



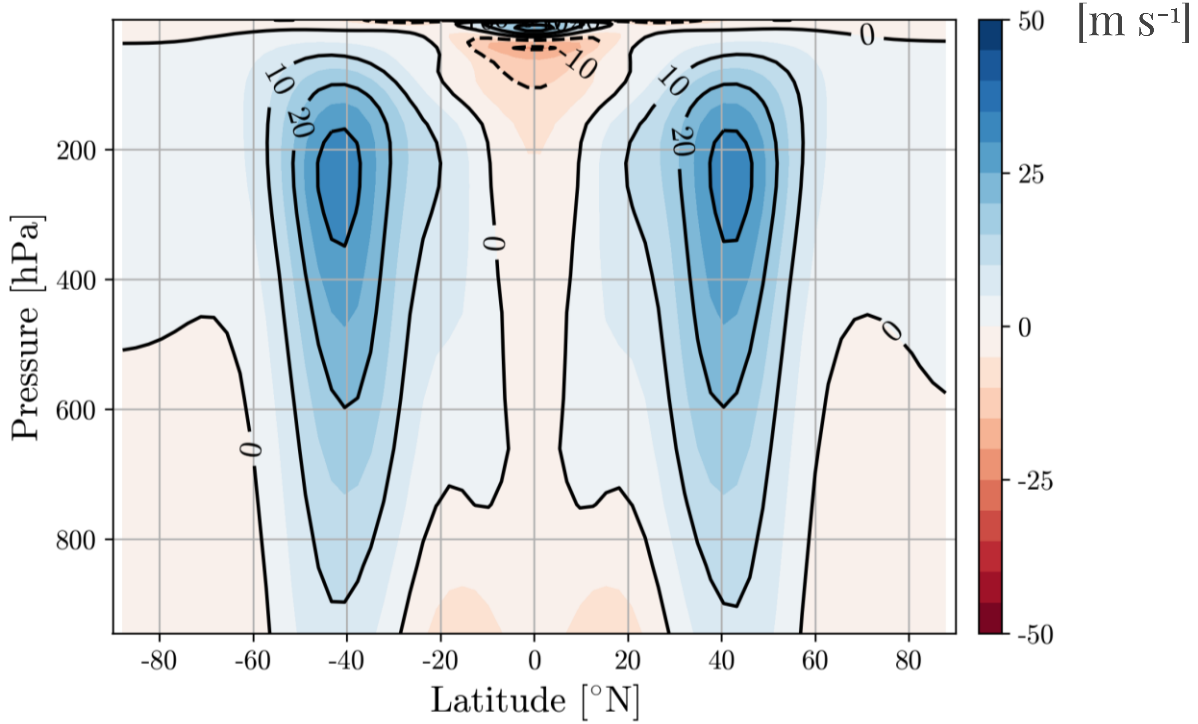
Dry Dynamical Core Models

Held & Suarez (1994)

Simulated Temperature



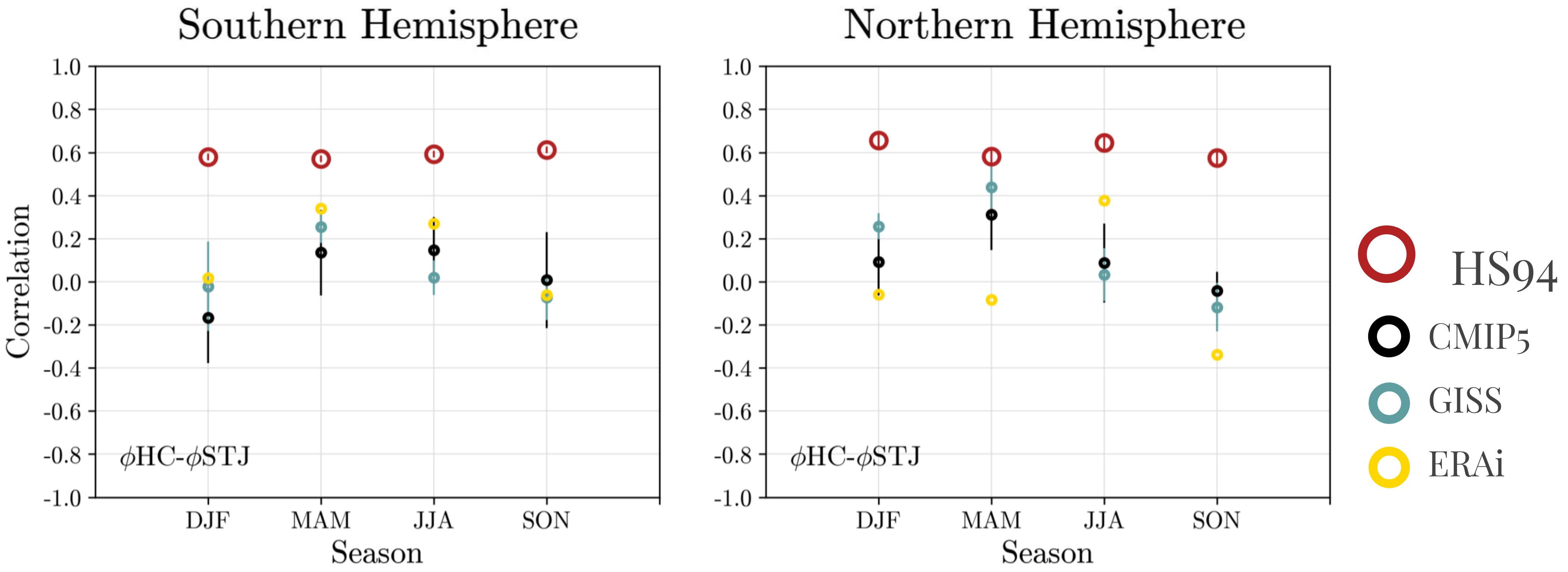
Simulated Wind



Equilibrium Temperature
(contour lines)

Dry Dynamical Core Models

- Held & Suarez (1994)
  Analytical, zonally symmetric T_{eq}



Dry Dynamical Core Models

Held & Suarez (1994)
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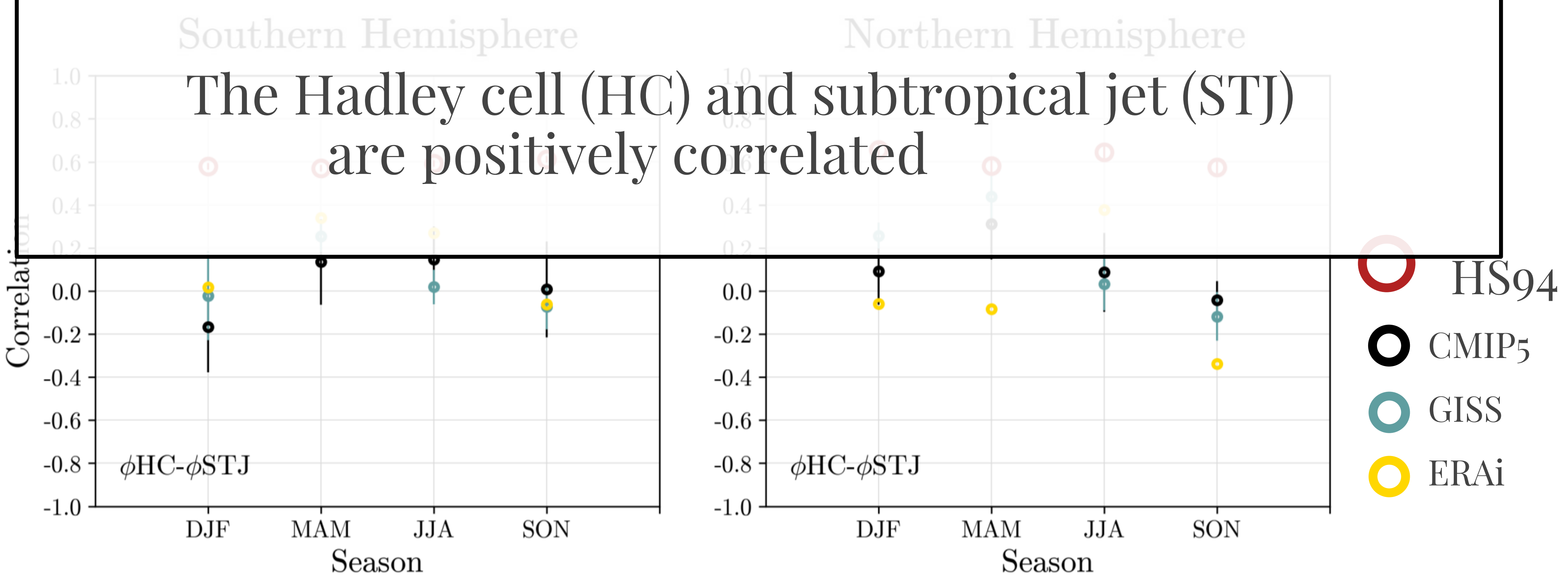


The Hadley cell (HC) and subtropical jet (STJ) are positively correlated

Dry Dynamical Core Models

Forced by an <u>equilibrium temperature profile</u>

$$\frac{\partial T}{\partial t} = \frac{T - T_{eq}}{\tau}$$

Classical Setup: Held & Suarez (1994)

T_{eq} set by an analytical function

$$T_{eq} = max\left\{T_{strat}, \left[T_0 - \delta_y (\sin\phi)^2 + T' - \delta_z \log\left(\frac{p}{p_0}\right)(\cos\phi)^2\right]\left(\frac{p}{p_0}\right)^{\kappa}\right\}$$

New Setup: Wu & Reichler (2018)

T_{eq} derived by iteration to improve accuracy

$$T_{eq} = T(\lambda, \phi, p, t)$$

Dry Dynamical Core Models

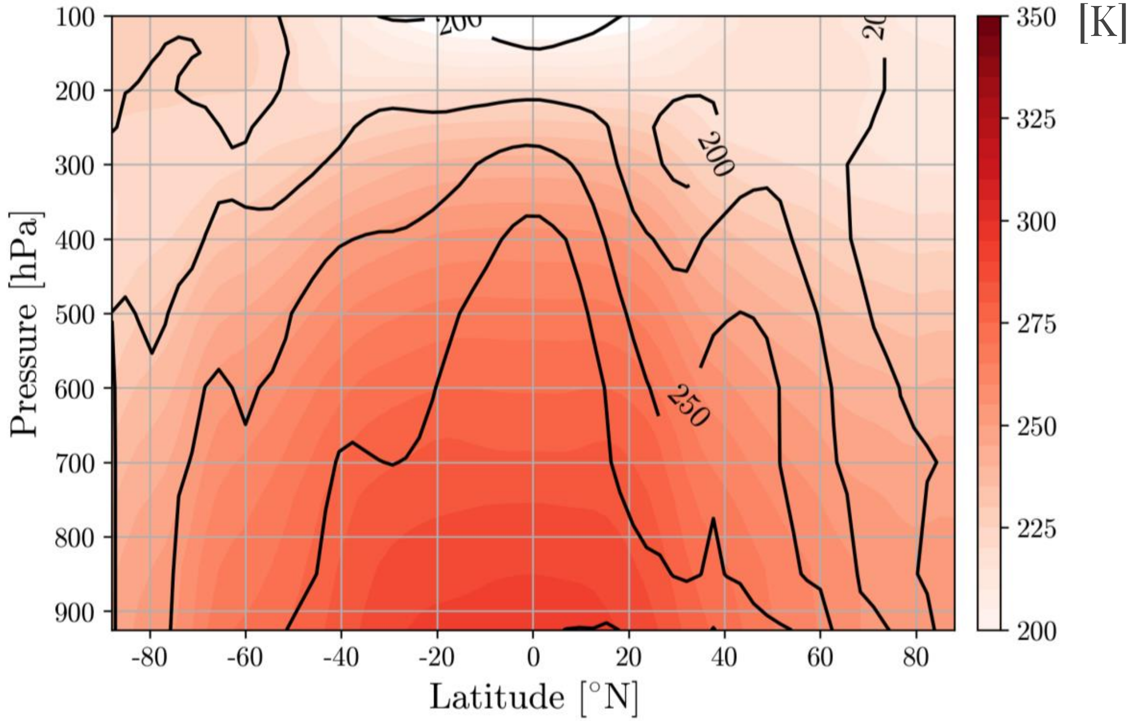
decreasing complexity →

	Wu & Reichler (2018)	Held & Suarez (1994)
T_{eq} Zonal Profile	Zonally varying	Zonally symmetric
Seasonality	Seasonally varying	No seasonality
Topography	Realistic topography	No topography
Stratosphere	Improved (Jucker et al. 2014)	

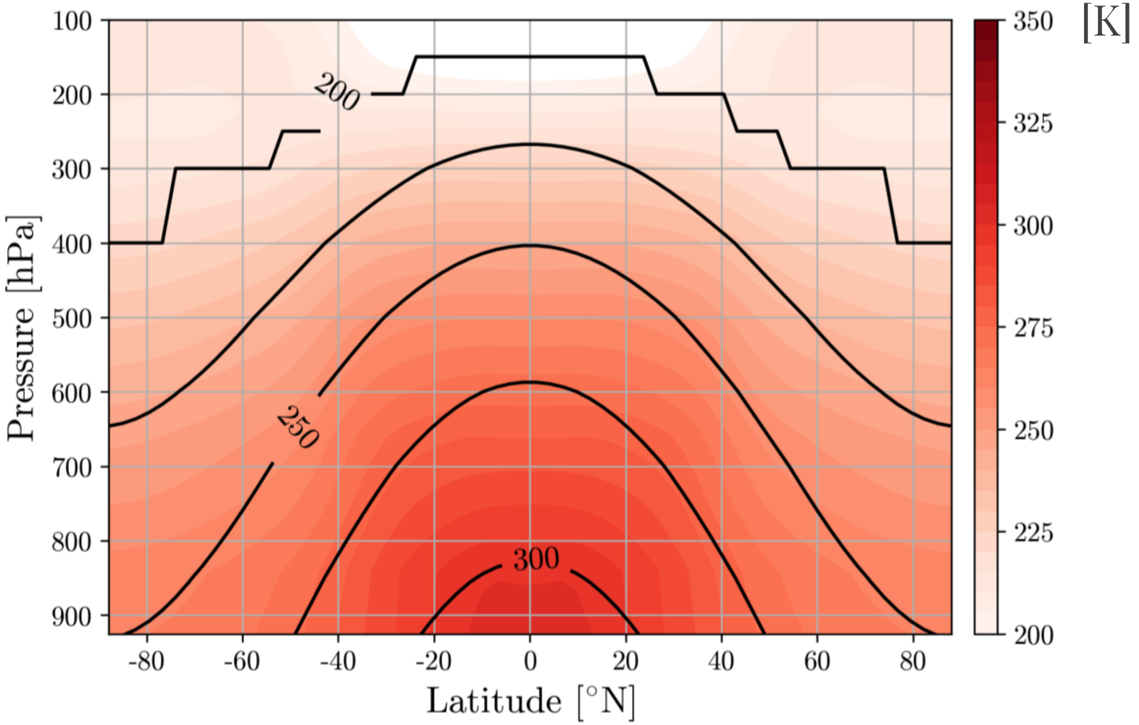
Dry Dynamical Core Models

decreasing complexity

Wu & Reichler (2018)



Held & Suarez (1994)



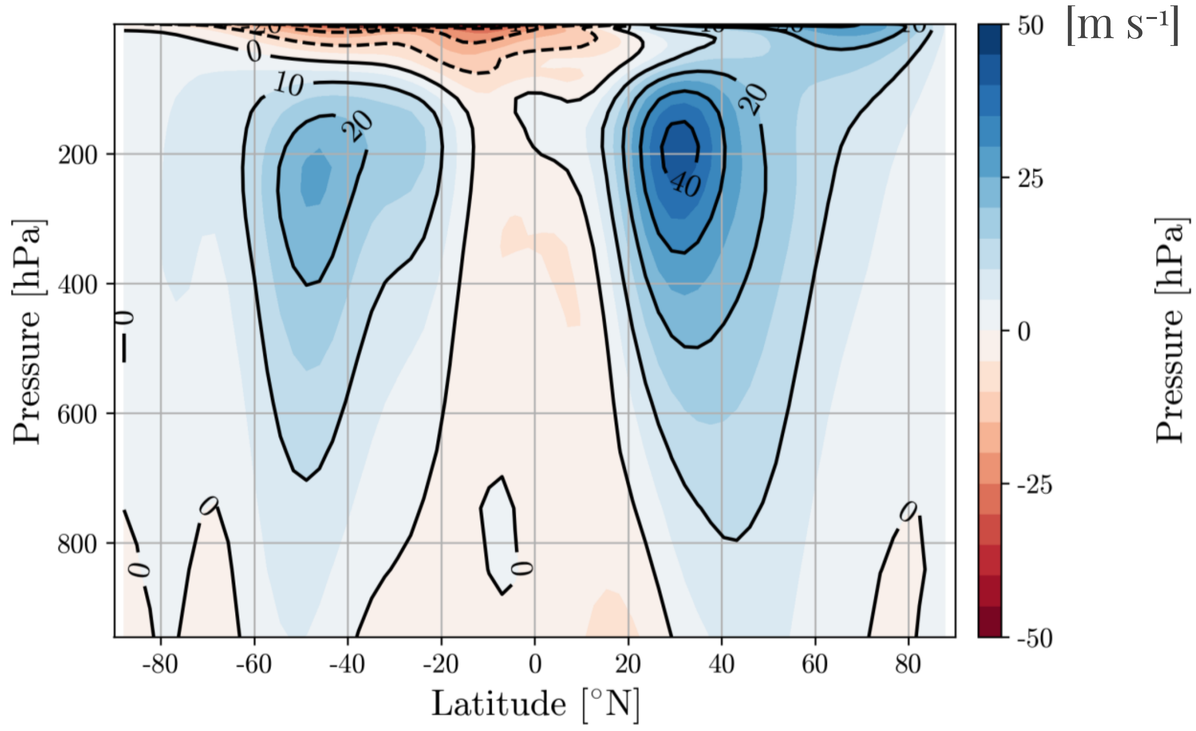
DJF
Climatology

Simulated Temperature,
Equilibrium Temperature (contour lines)

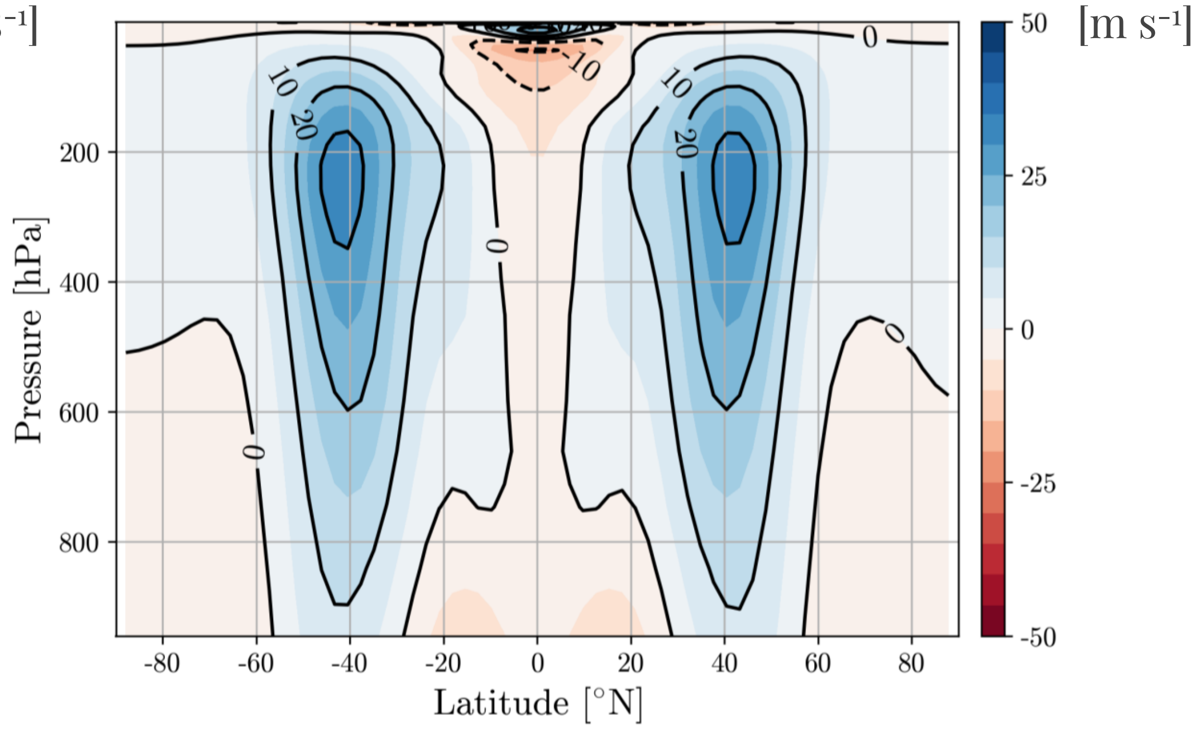
Dry Dynamical Core Models

decreasing complexity

Wu & Reichler (2018)



Held & Suarez (1994)



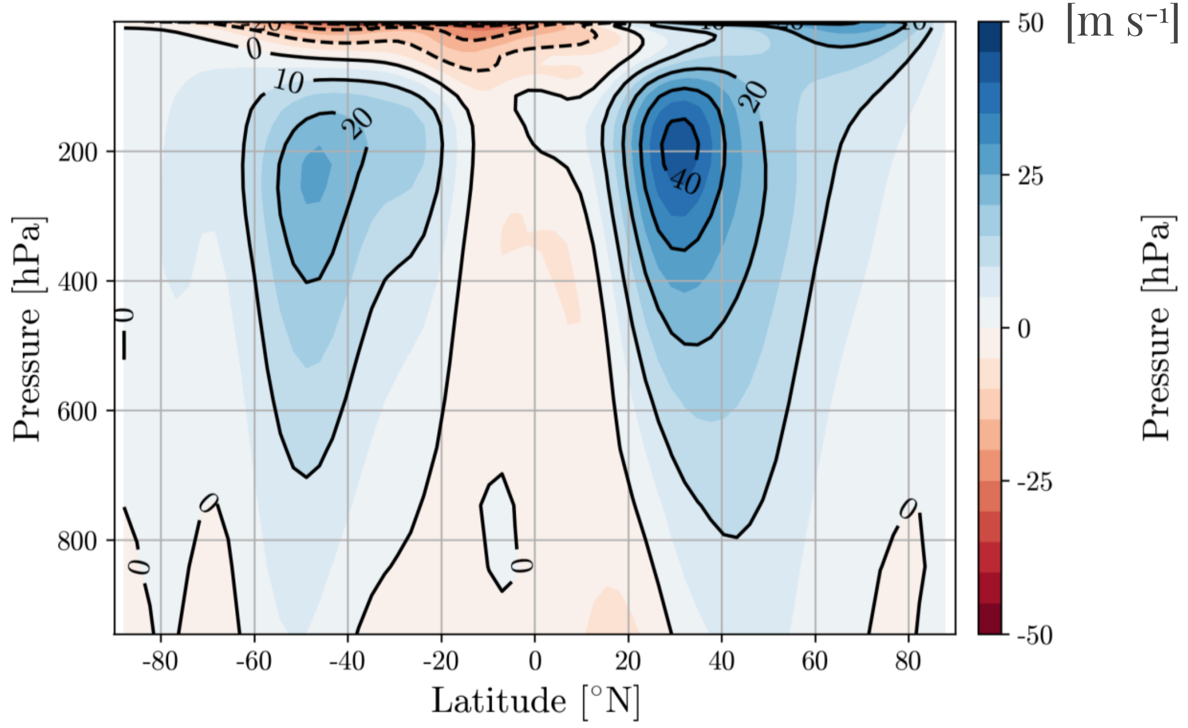
DJF
Climatology

Simulated Wind

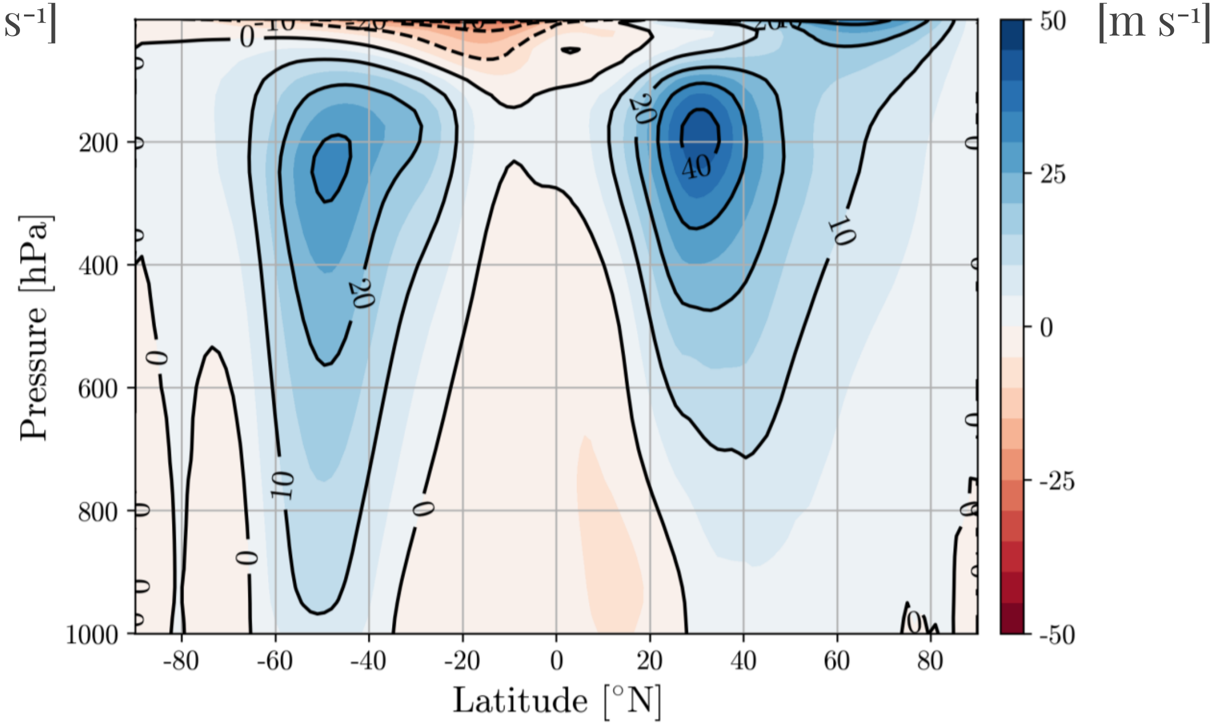
Dry Dynamical Core Models

decreasing complexity

Wu & Reichler (2018)



ERA-interim Reanalysis

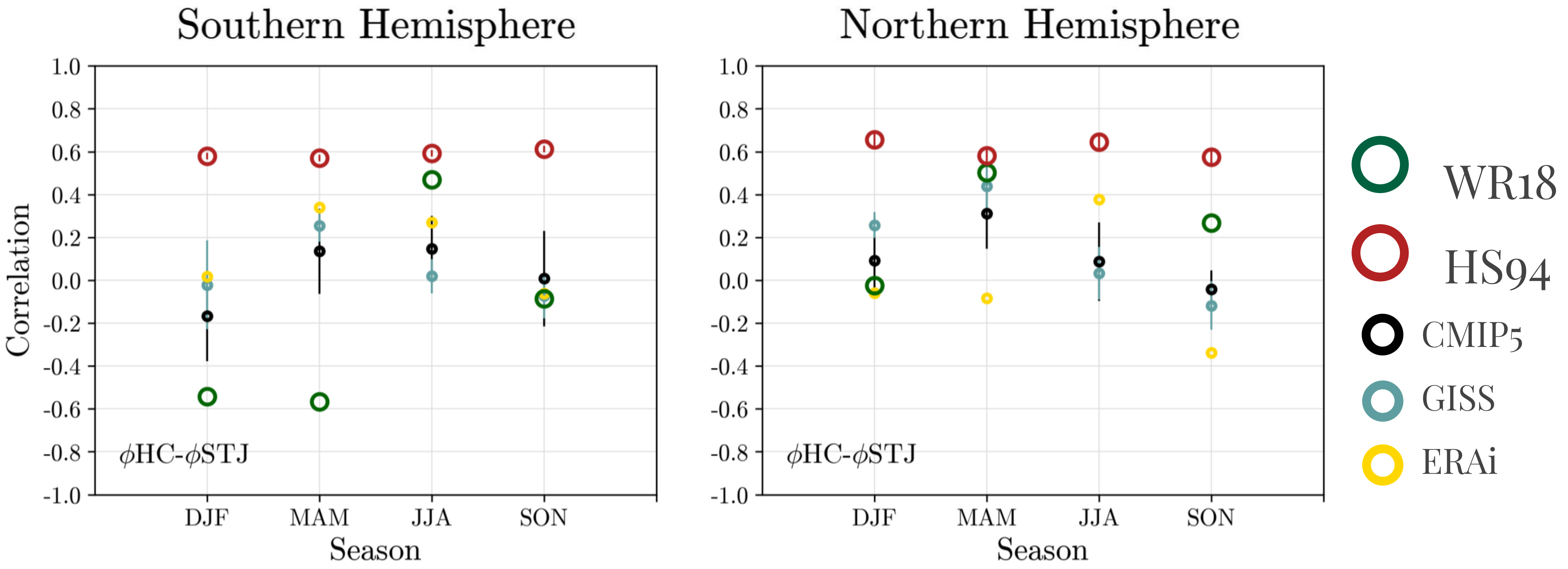


DJF
Climatology

Simulated Wind

Dry Dynamical Core Models

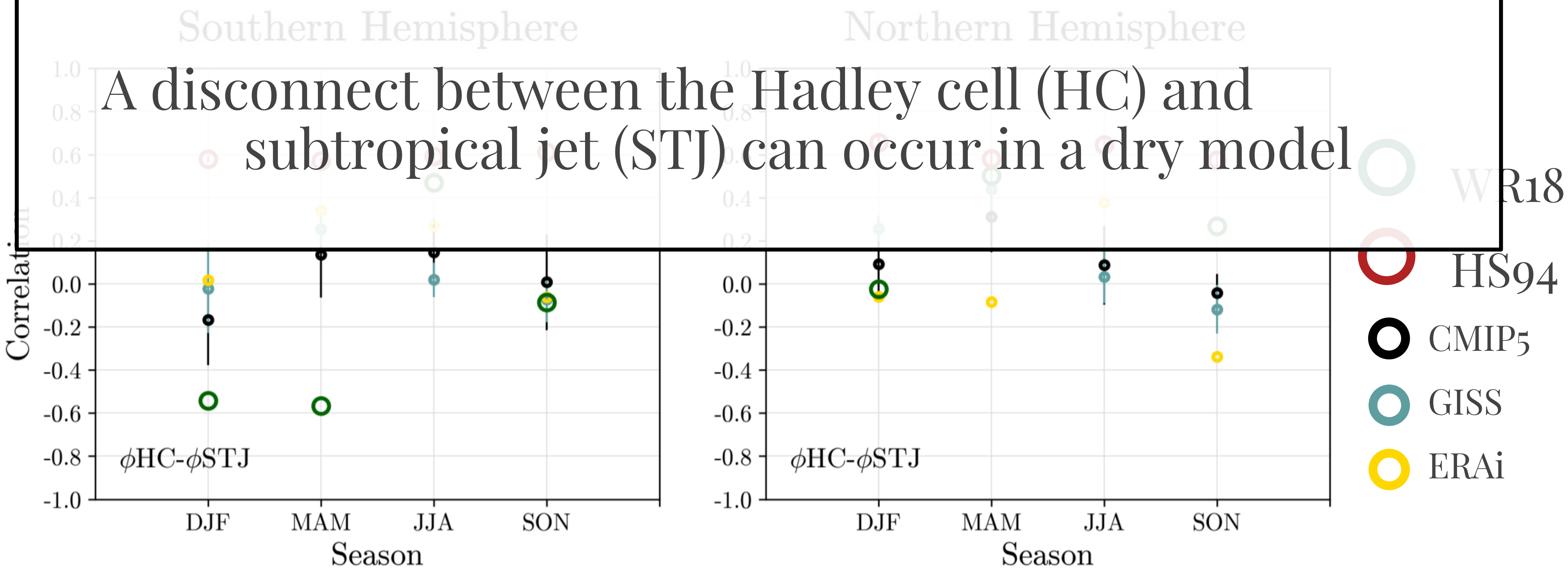
- Wu & Reichler (2018)
  Derived by iteration, zonally and seasonally-varying T_{eq}



Dry Dynamical Core Models

- Wu & Reichler (2018)
  Derived by iteration, zonally and seasonally-varying T_{eq}

A disconnect between the Hadley cell (HC) and subtropical jet (STJ) can occur in a dry model



Dry Dynamical Core Models

A disconnect between the Hadley cell (HC) and subtropical jet (STJ) can occur in a dry model

Follow-up Question:

Is this a result of zonal variability in the "forcing"?

Dry Dynamical Core Models

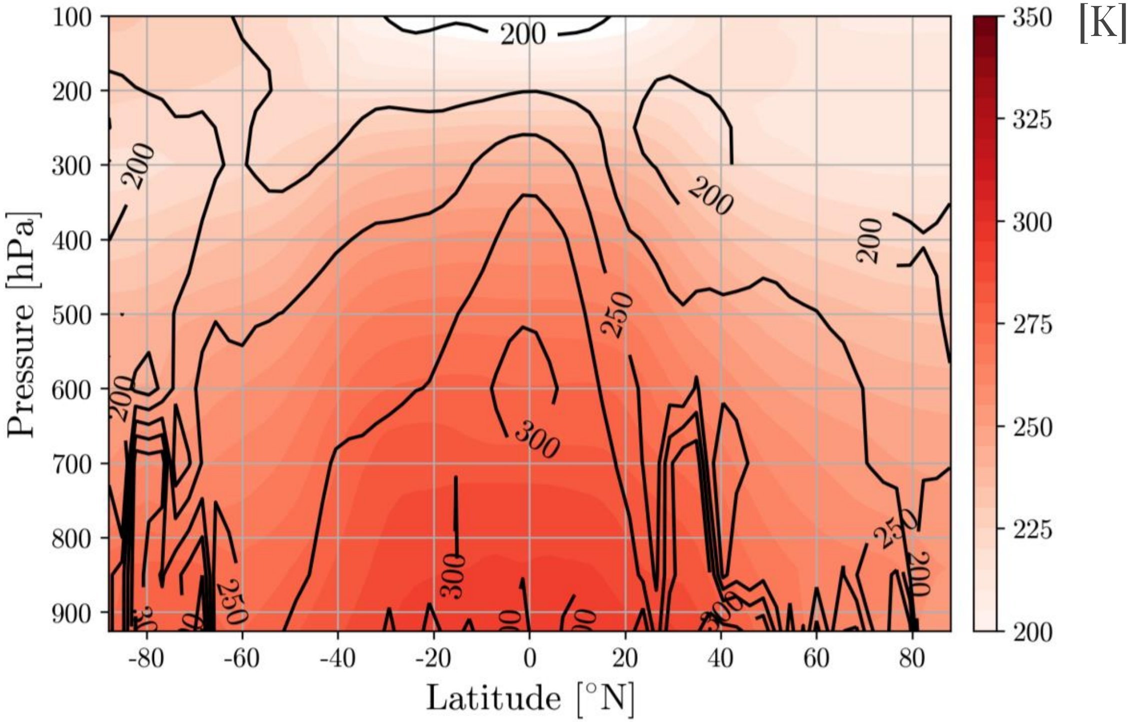
decreasing complexity →

	Wu & Reichler (2018)	Wu & Reichler (2018), Zonal	Held & Suarez (1994)
T_{eq} Zonal Profile	Zonally varying	Zonally symmetric	Zonally symmetric
Seasonality	Seasonally varying	Seasonally varying	No seasonality
Topography	Realistic topography	No topography	No topography
Stratosphere	Improved (Jucker et al. 2014)	Improved (Jucker et al. 2014)	

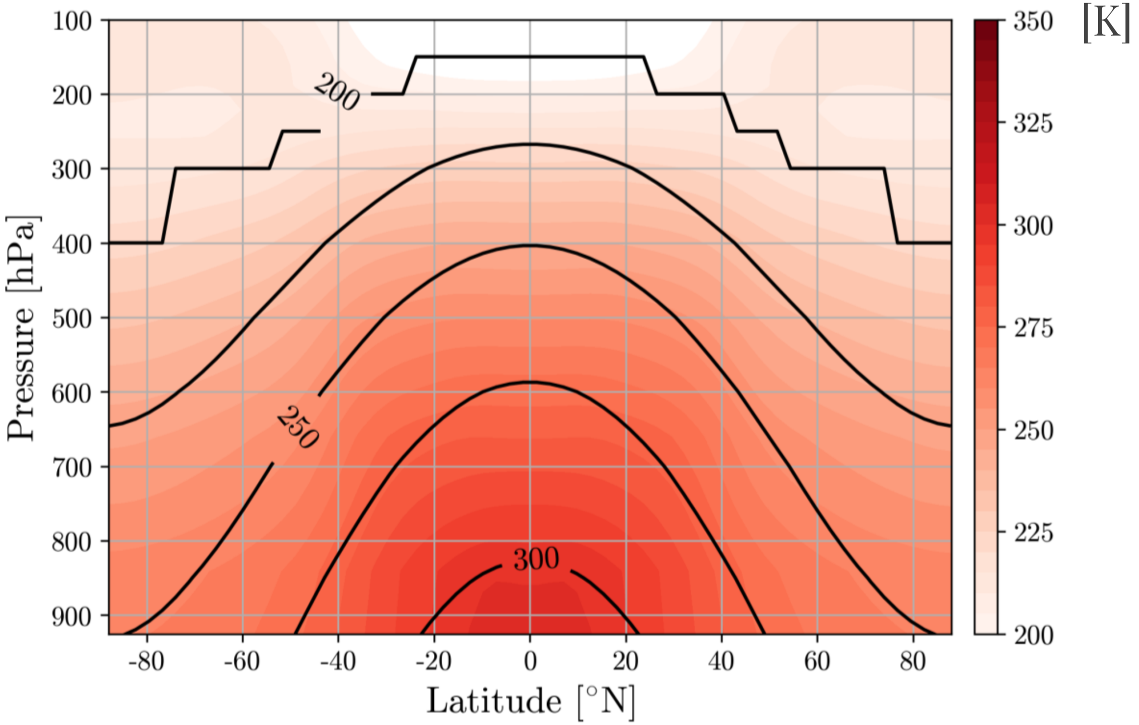
Dry Dynamical Core Models

decreasing complexity

Zonal Wu & Reichler (2018)



Held & Suarez (1994)



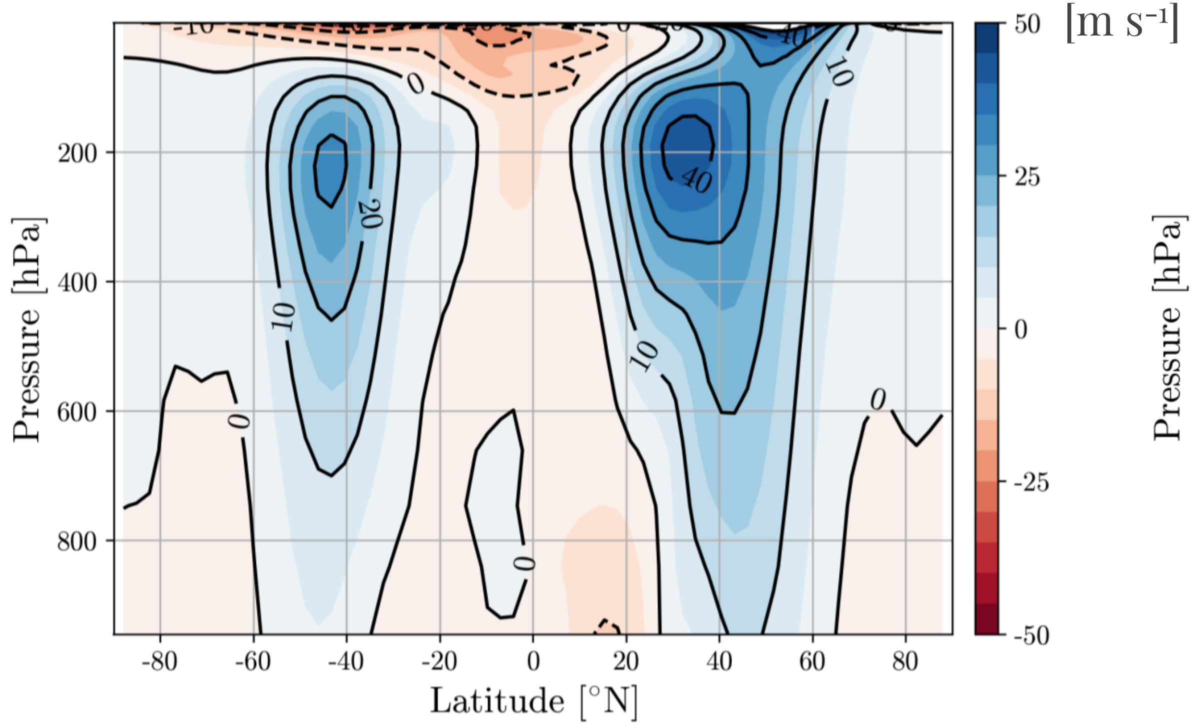
DJF
Climatology

Simulated Temperature,
Equilibrium Temperature (contour lines)

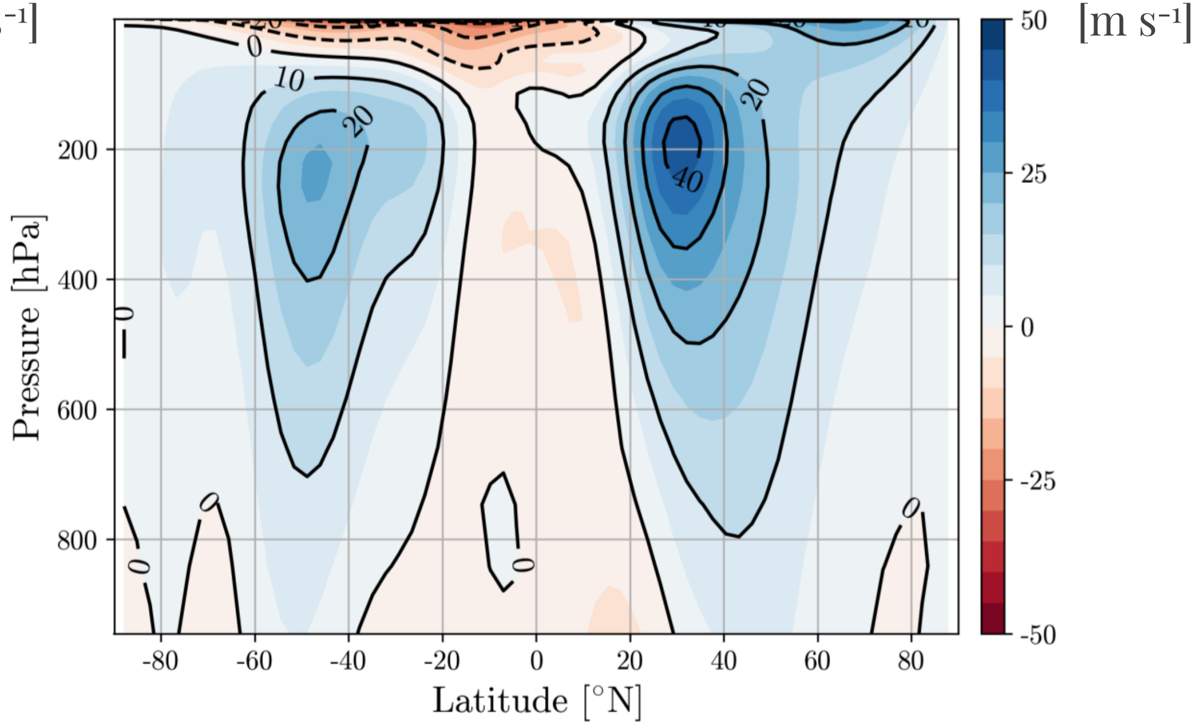
Dry Dynamical Core Models

decreasing complexity

Zonal Wu & Reichler (2018)



3D Wu & Reichler (2018)



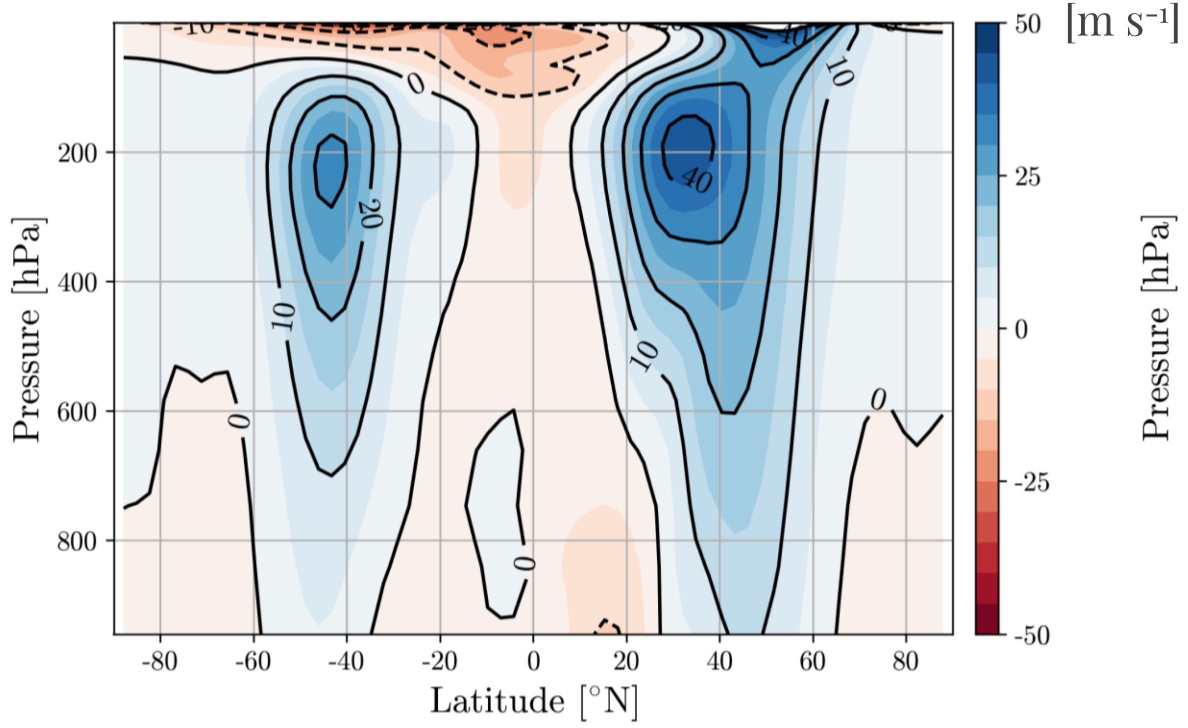
DJF
Climatology

Simulated Wind

Dry Dynamical Core Models

decreasing complexity

Zonal Wu & Reichler (2018)



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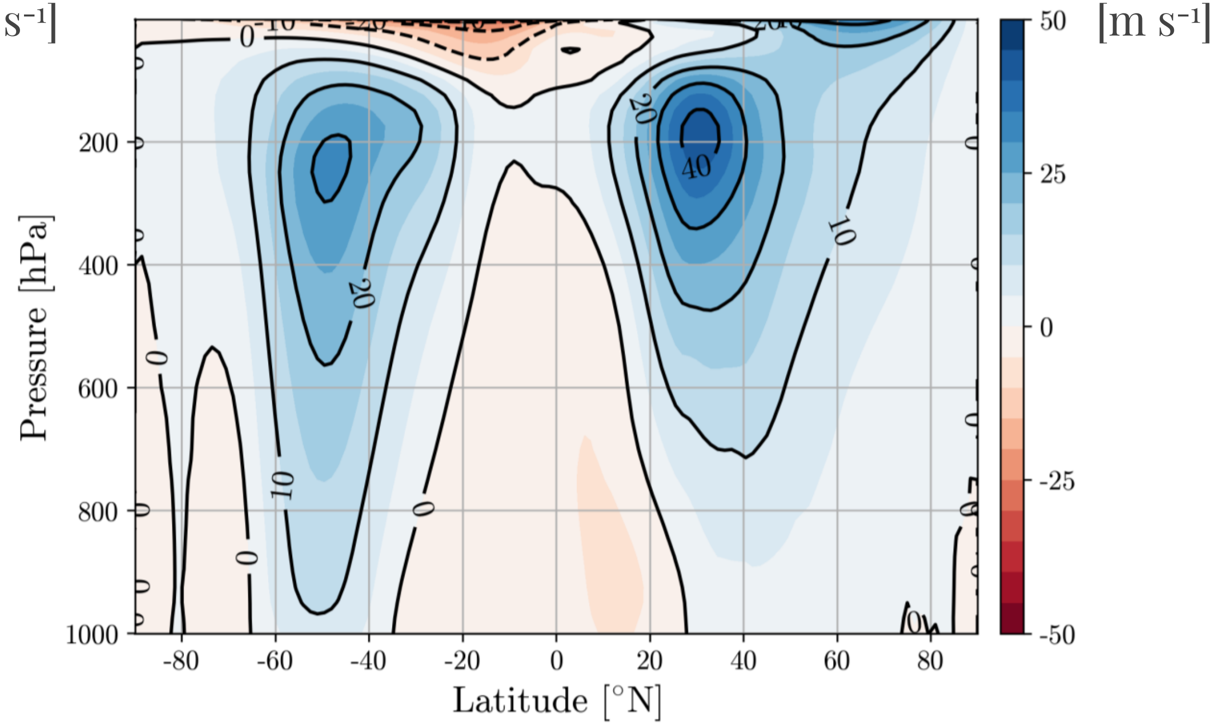

DJF
Climatology

Simulated Wind

Dry Dynamical Core Models

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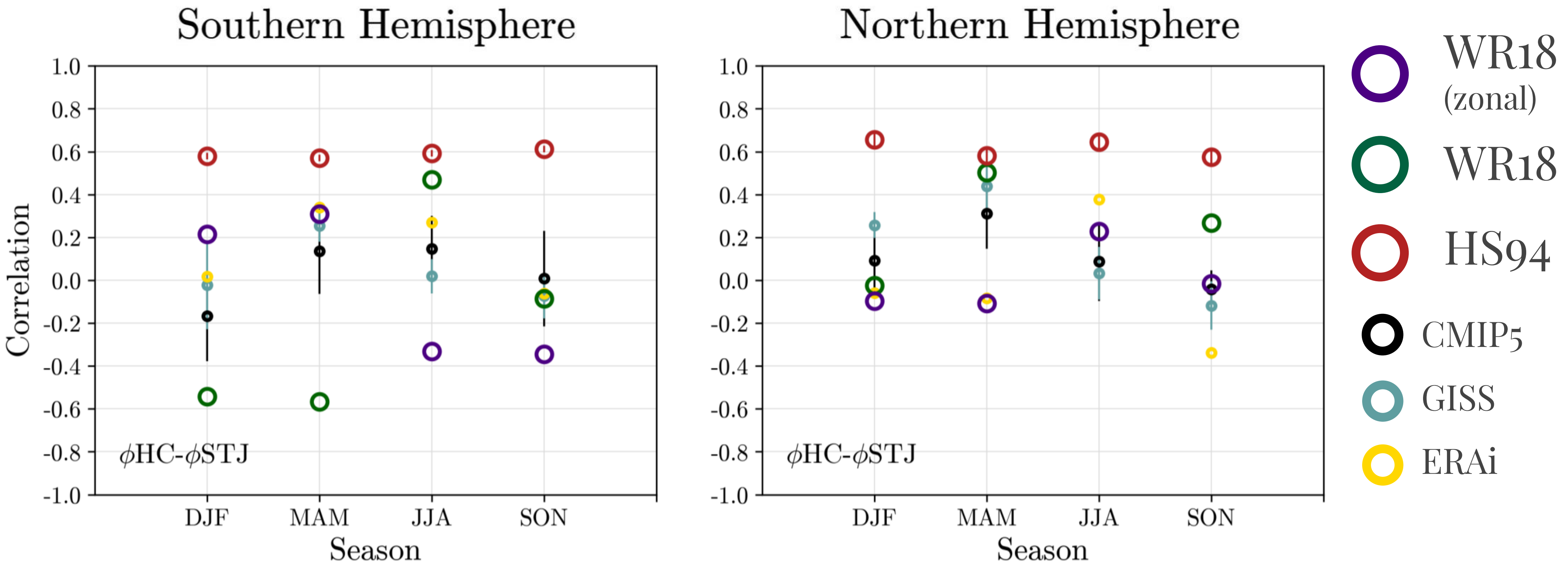
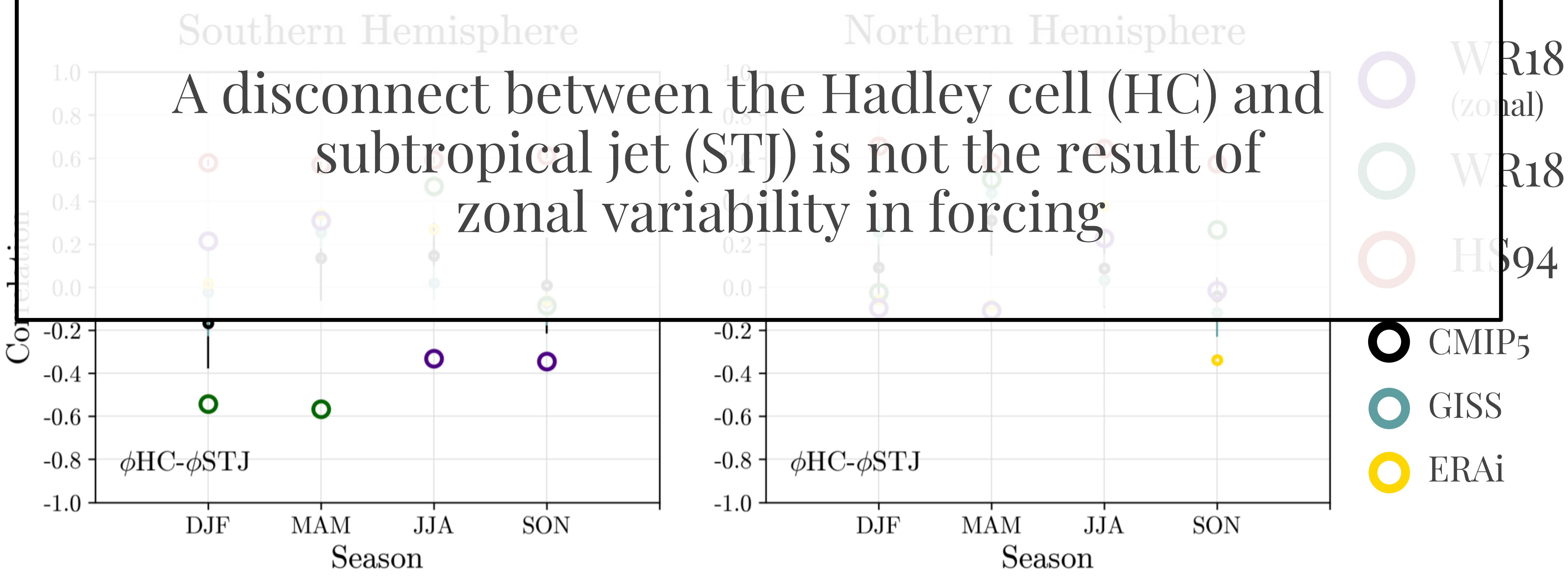
  Derived by iteration, zonally-symmetric, seasonally-varying T_{eq}



Dry Dynamical Core Models

- Zonal Wu & Reichler (2018)
  Derived by iteration, zonally-symmetric, seasonally-varying T_{eq}

A disconnect between the Hadley cell (HC) and subtropical jet (STJ) is not the result of zonal variability in forcing



Dry Dynamical Core Models

The Hadley cell (HC) and subtropical jet (STJ) are positively correlated in the classical Held & Suarez (1994) setup

BUT! →

Dry Dynamical Core Models

The Hadley cell (HC) and subtropical jet (STJ) are positively correlated in the classical Held & Suarez (1994) setup

BUT! →

A disconnect between the HC and STJ can occur in a dry model

Dry Dynamical Core Models

The Hadley cell (HC) and subtropical jet (STJ) are positively correlated in the classical Held & Suarez (1994) setup

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↓

It is not the result of zonal variability in the forcing

Dry Dynamical Core Models

The Hadley cell (HC) and subtropical jet (STJ) are positively correlated in the classical Held & Suarez (1994) setup

BUT! →

A disconnect between the HC and STJ can occur in a dry model

It is not the result of zonal variability in the forcing

Follow-up Question:

What are the differences in the basic state?

Dry Dynamical Core Models

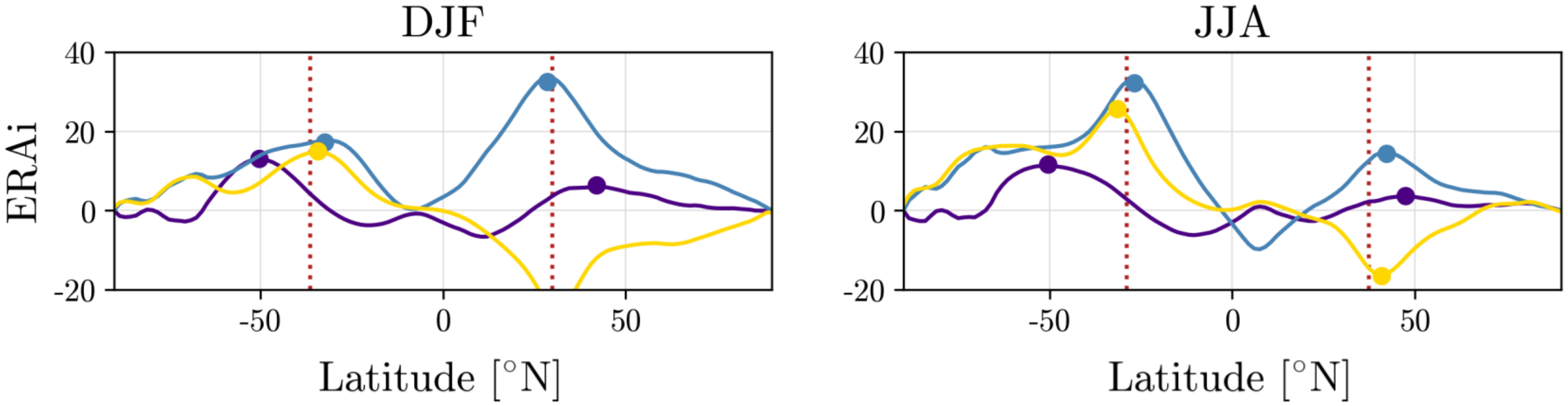
Basic State Analysis

u_{adj} — ϕSTJ

$u_{850\ hPa}$ — ϕEDJ

dT/dy — $\phi \frac{dT}{dy}$

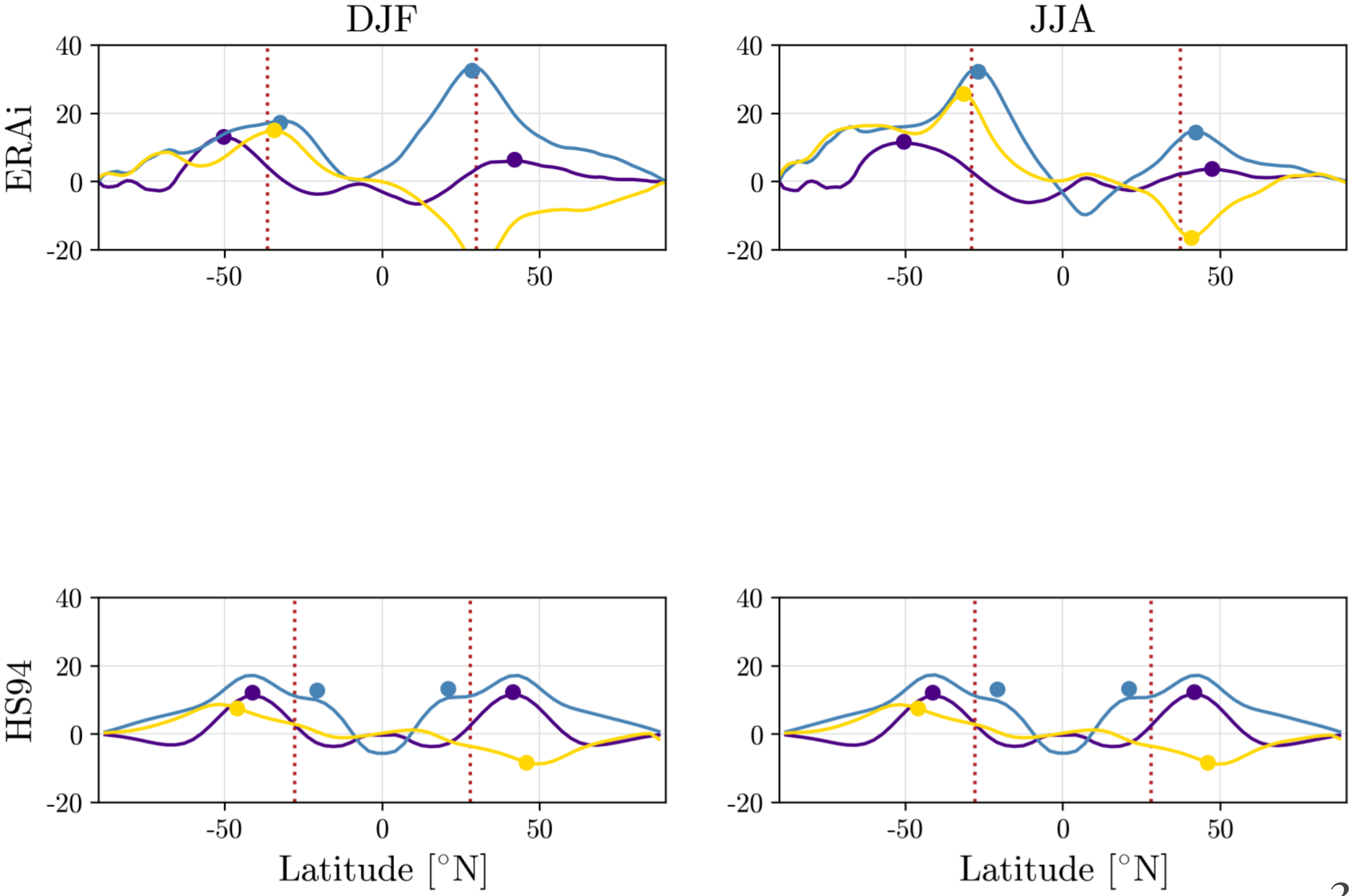
ϕHC



Dry Dynamical Core Models

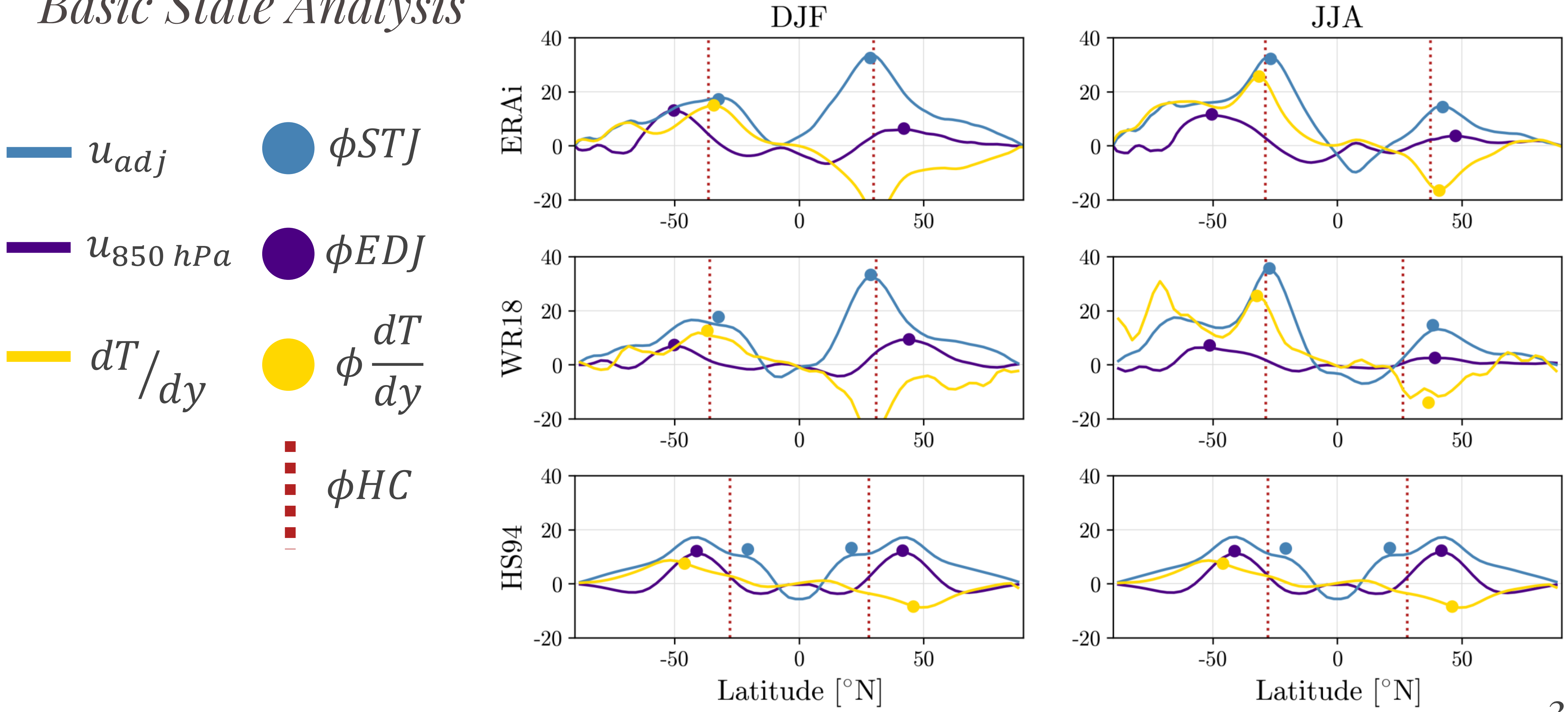
Basic State Analysis

- u_{adj}
- $u_{850\ hPa}$
- $dT/_{dy}$
- ϕSTJ
- ϕEDJ
- $\phi \frac{dT}{dy}$
- ϕHC



Dry Dynamical Core Models

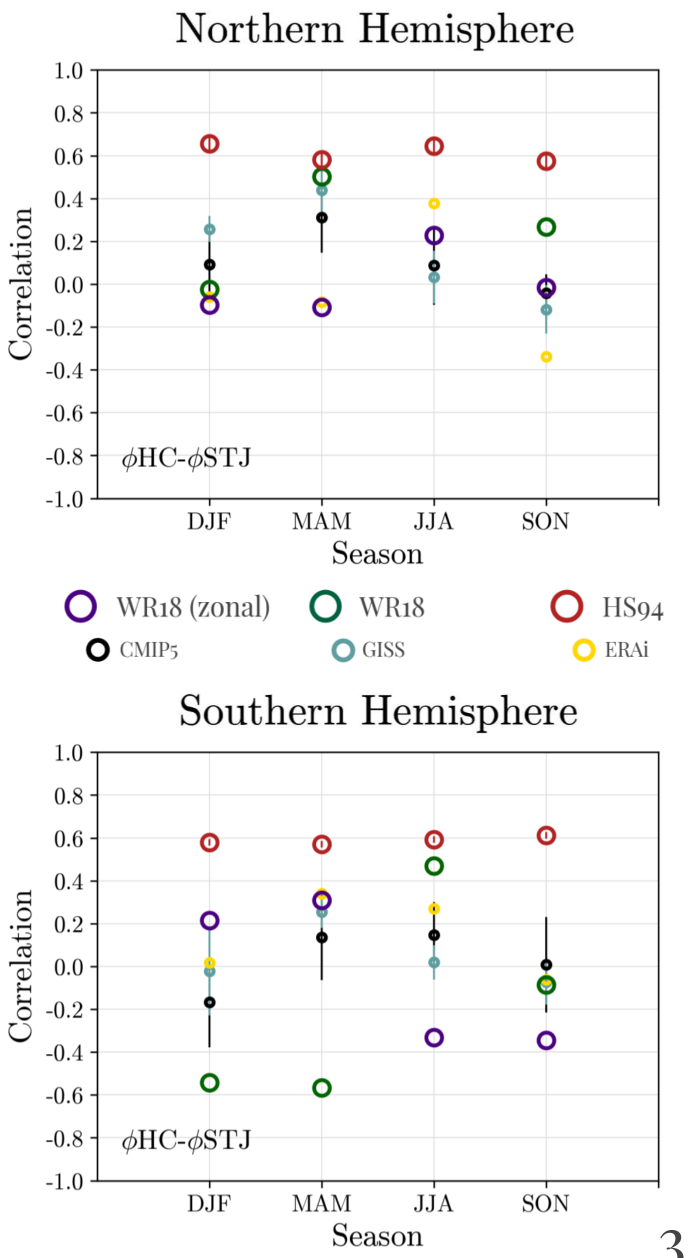
Basic State Analysis



Idealized Modelling

Conclusion:

A disconnect between the STJ and HC can occur in a fully dry atmospheric model when the model simulates a realistic STJ



Conclusions

Conclusions

	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)

Key Points:

1. The subtropical jet (STJ) is not coupled to the Hadley Cell (HC)

Conclusions

	Southern Hemisphere					Northern Hemisphere				
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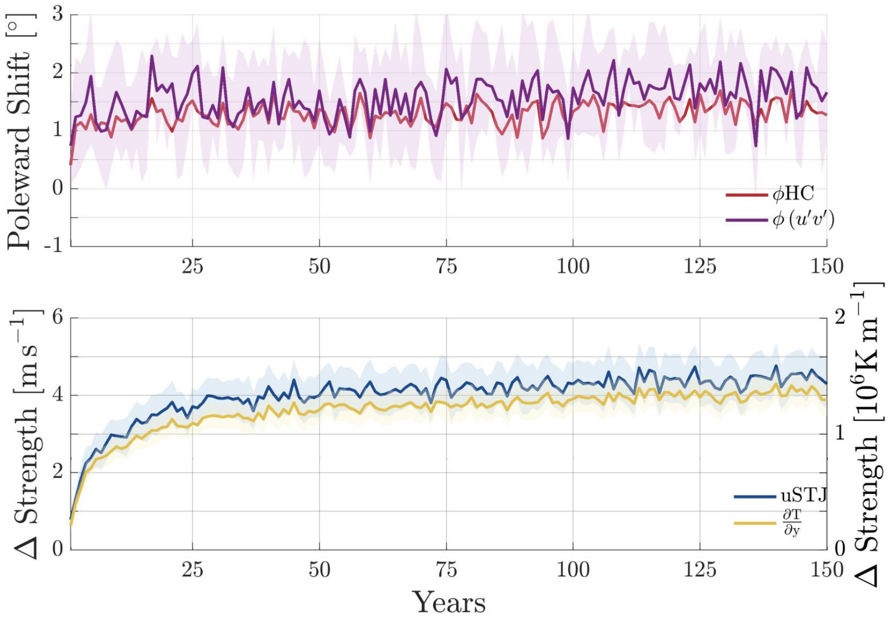
Key Points:

1. The subtropical jet (STJ) is not coupled to the Hadley Cell (HC)

2. The HC and STJ's behavior is consistent with physical balances observed in the atmosphere



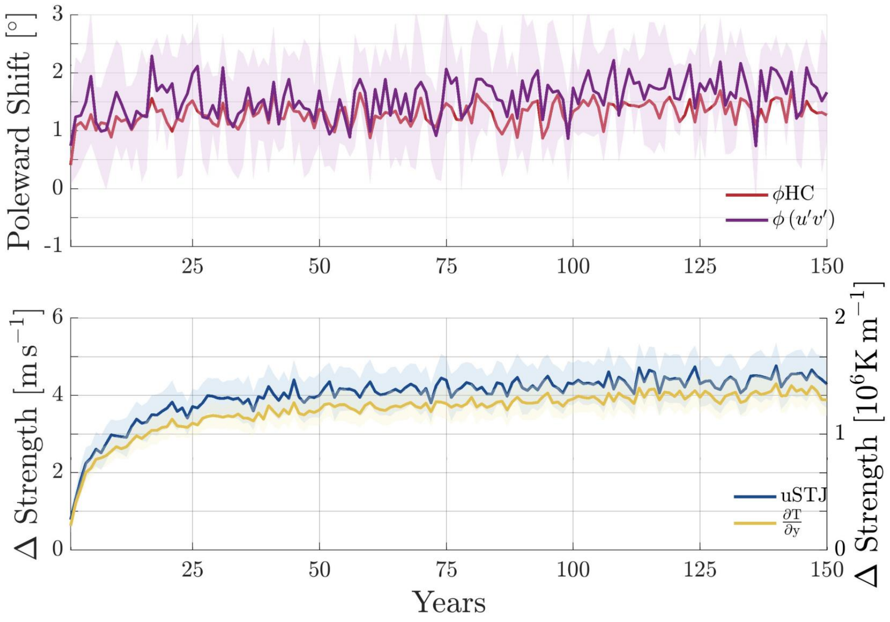
Conclusions

	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)

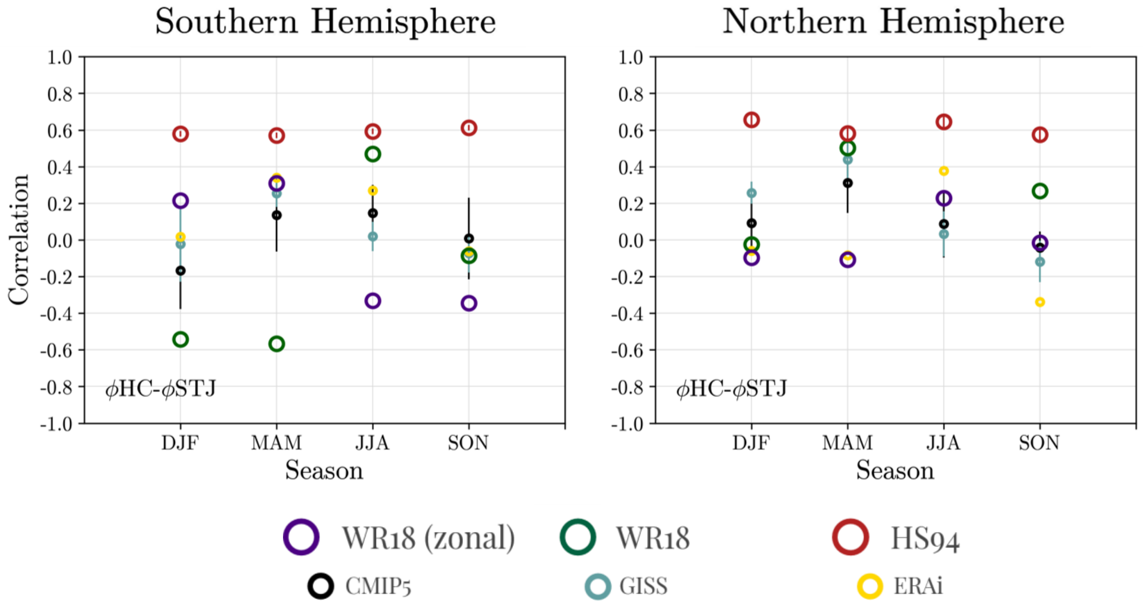
Key Points:

1. The subtropical jet (STJ) is not coupled to the Hadley Cell (HC)

2. The HC and STJ's behavior is consistent with physical balances observed in the atmosphere



3. A disconnect between the STJ and HC can occur in a fully dry atmospheric model when the model simulates a realistic STJ



Conclusions

Key Points:

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2. The HC and STJ's behavior is consistent with physical balances observed in the atmosphere

3. A disconnect between the STJ and HC can occur in a fully dry atmospheric model when the model simulates a realistic STJ

Hypothesis:

A coupling between the Hadley cell and subtropical jet occurs when eddy influence on the subtropical thermal wind balance is non-negligible

Continuing Work

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Balances in Idealized Models

What is the relationship between the midlatitude eddies and subtropical thermal wind balance in the different simulations?

Continuing Work

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What is the relationship between the midlatitude eddies and subtropical thermal wind balance in the different simulations?

Non-metric Analysis

What are the limitations of metric analysis?

Will analysis of atmospheric fields provide greater insight into the system dynamics?

Continuing Work

Questions?

Hypothesis:

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Balances in Idealized Models

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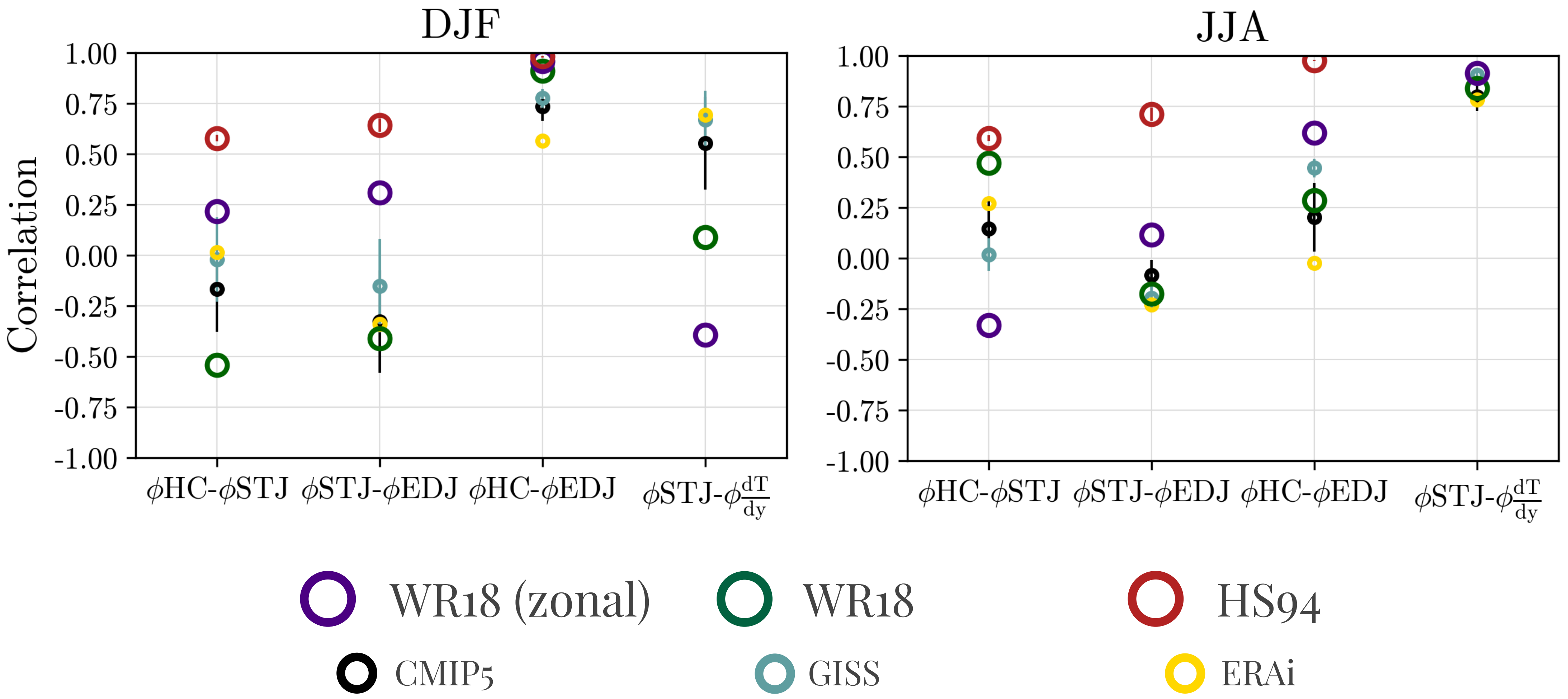
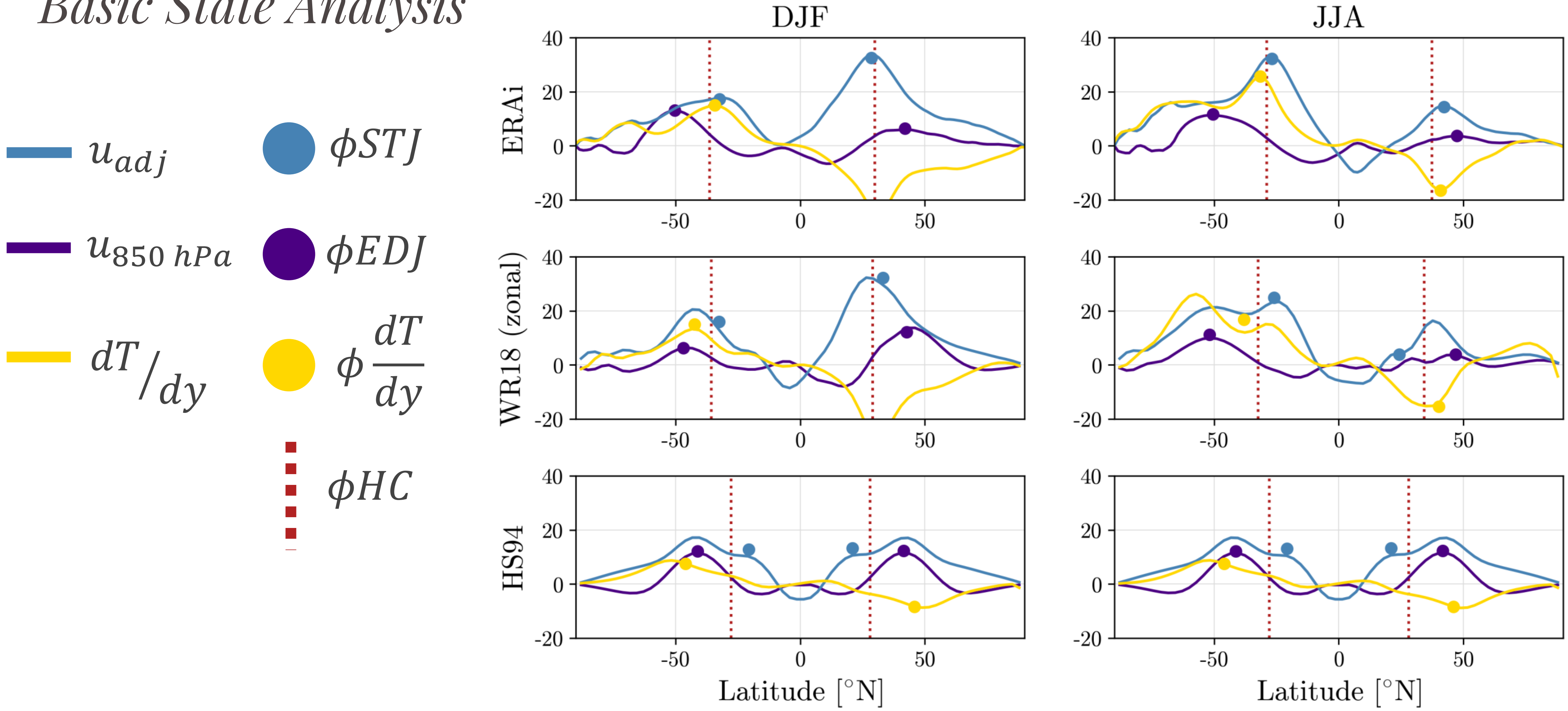
Extra Slides

Dry Dynamical Core Models



Dry Dynamical Core Models

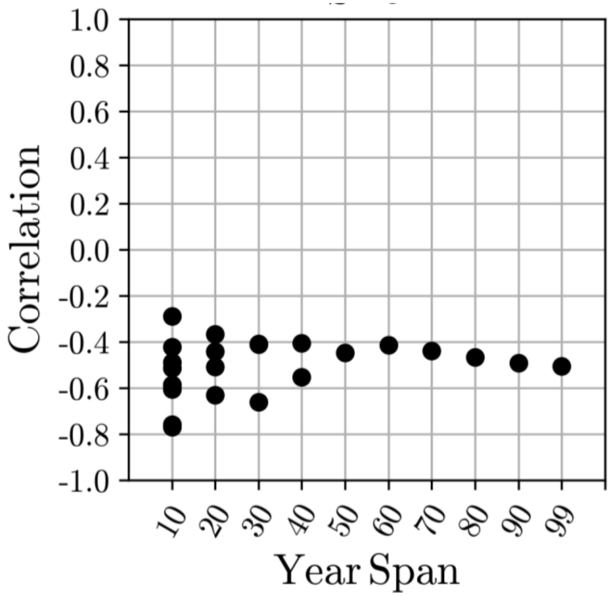
Basic State Analysis



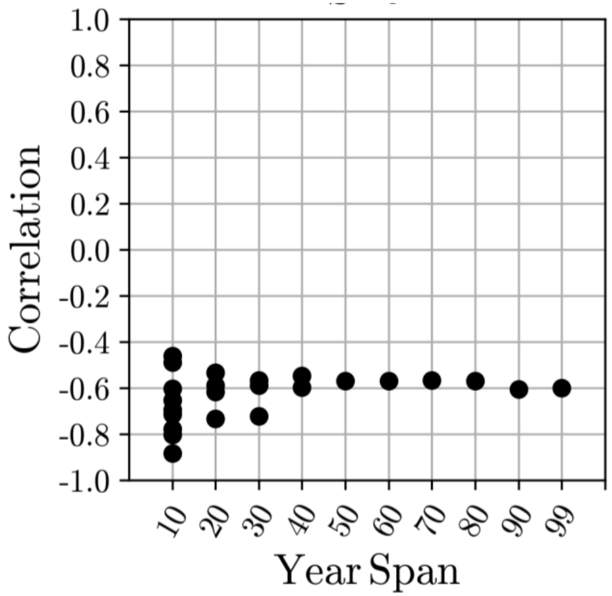
Dry Dynamical Core Models

Correlation Convergence

Wu & Reichler (2018)



Zonal Wu & Reichler (2018)



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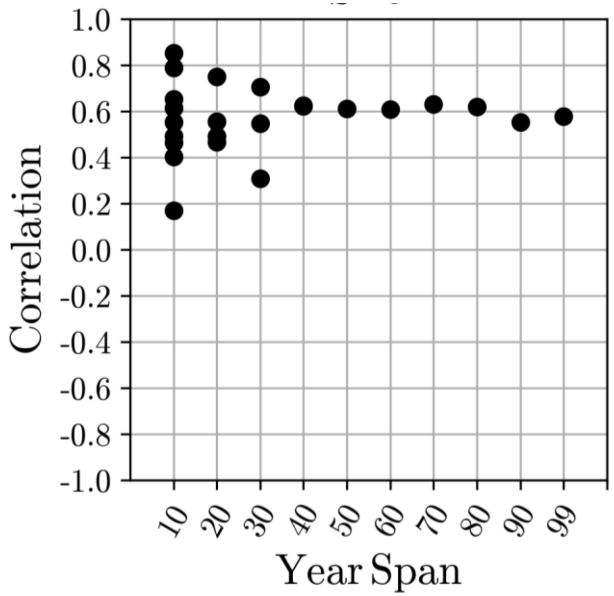


GISS-E2.1 Model

NASA Goddard Institute for Space Studies' Global Climate Model

abruptNxCO2

Abrupt multiplying of CO2, held fixed

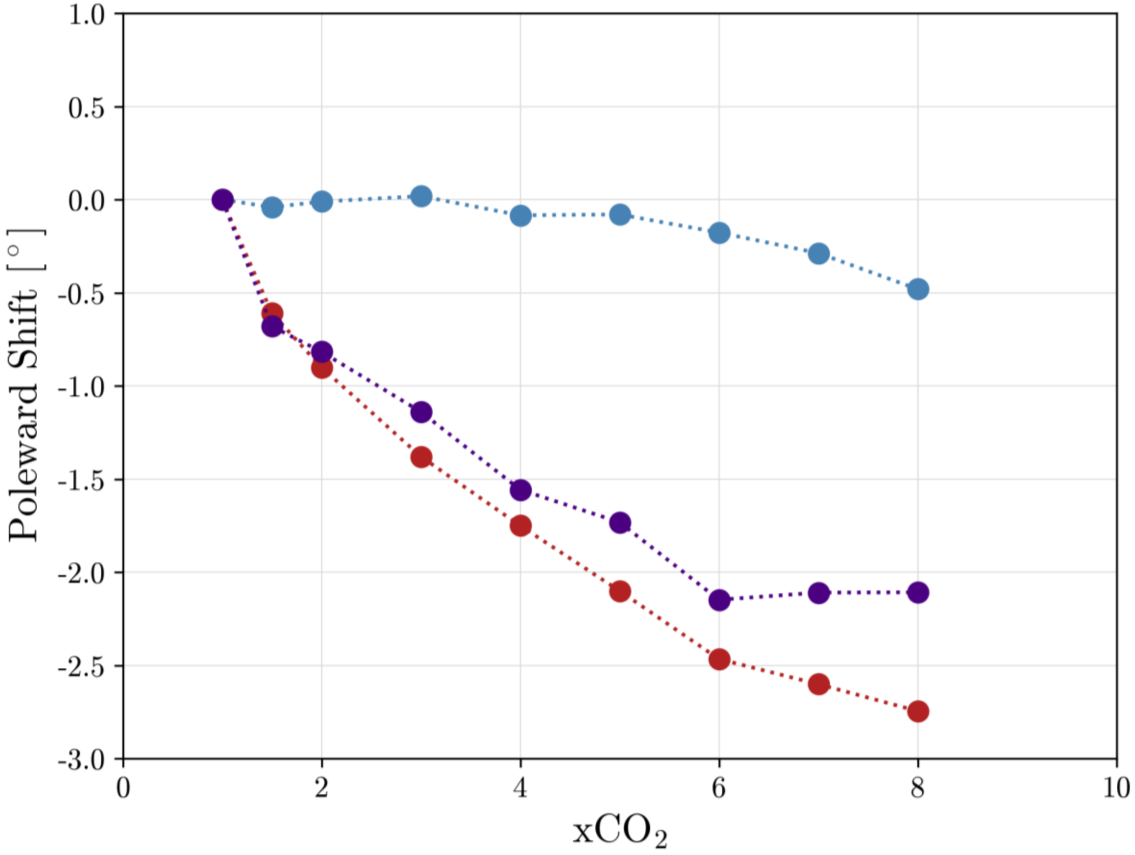
1xCO2	5xCO2
1.5xCO2	6xCO2
2xCO2	7xCO2
3xCO2	8xCO2
4xCO2	

provided by
Clara Orbe and Ivan Mitevski

ϕSTJ

ϕEDJ

ϕHC

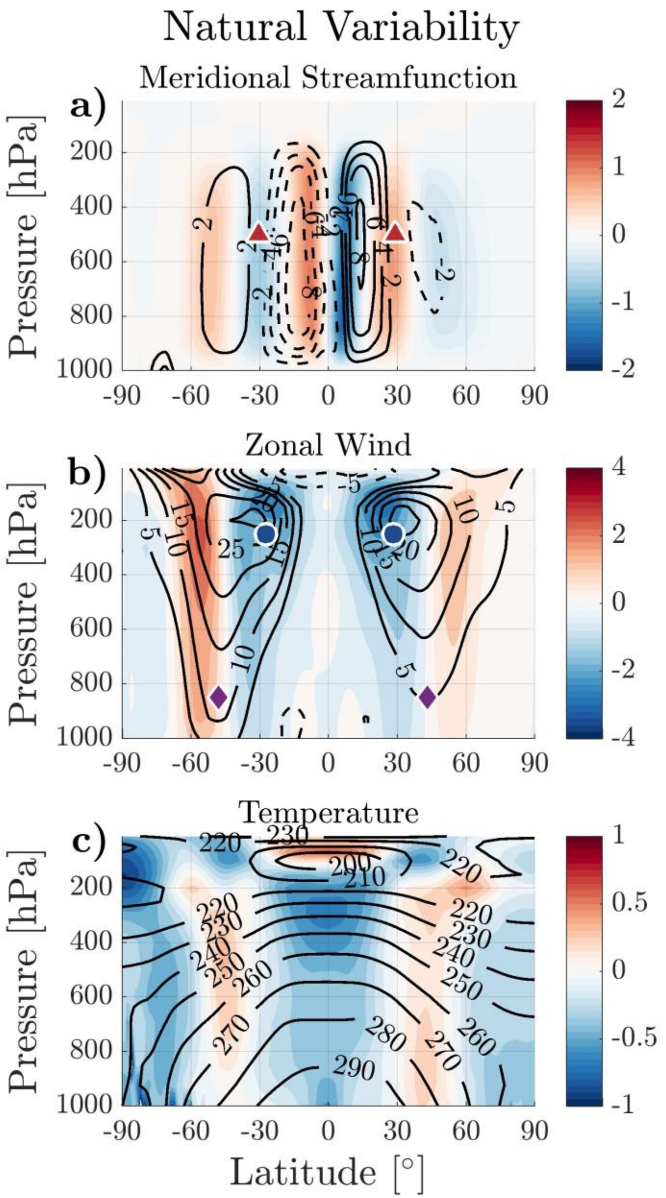


CMIP5: Cooling

Hadley cell:
– Expands
– Weakens

Eddy-driven jet:
– Shifts poleward
– Strengthens

Subtropical jet:
– Shifts poleward
– Weakens



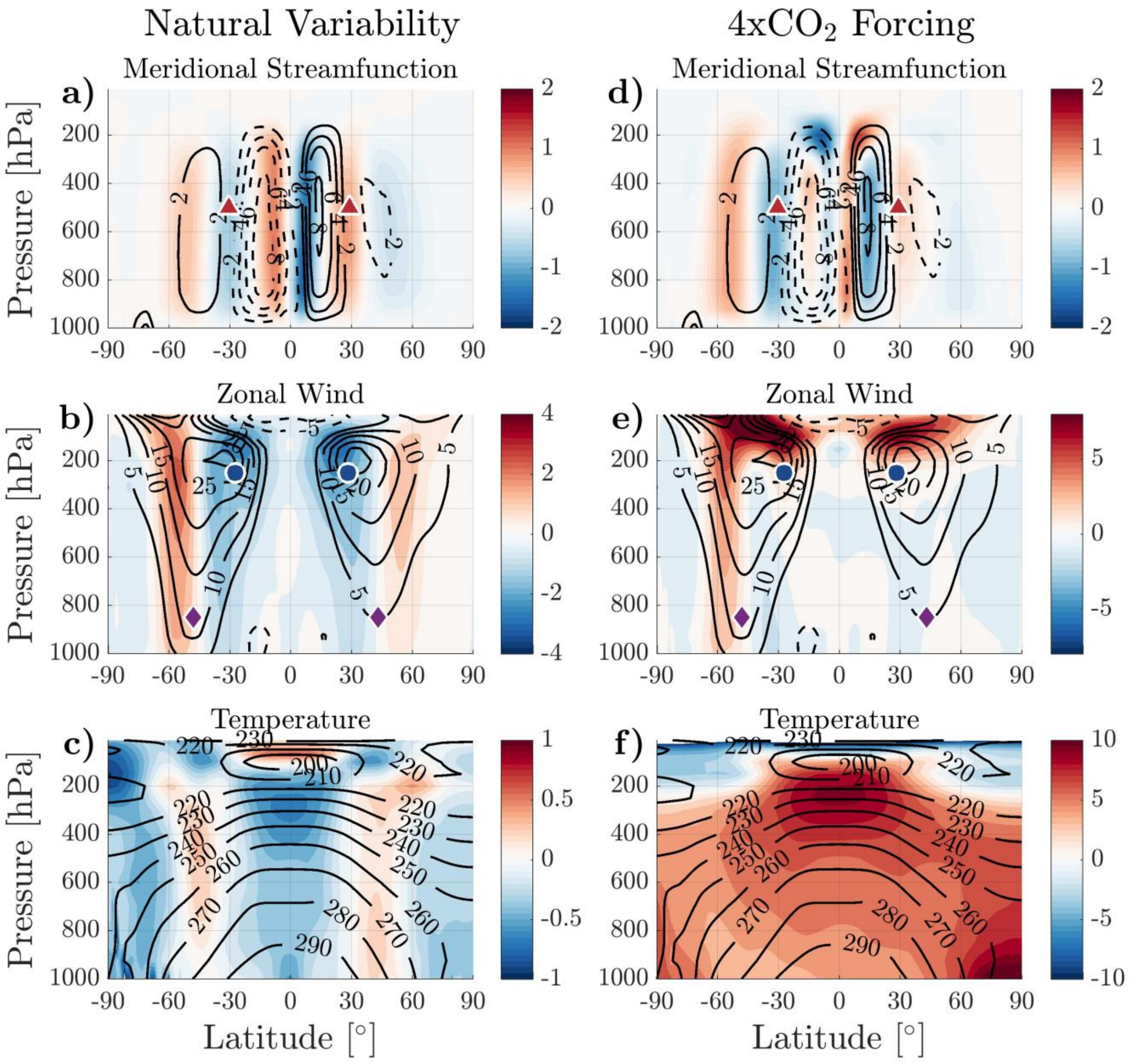
Menzel et al. 2019

CMIP5: Warming

Hadley cell:
– Expands
– Weakens

Eddy-driven jet:
– Shifts poleward
– Strengthens

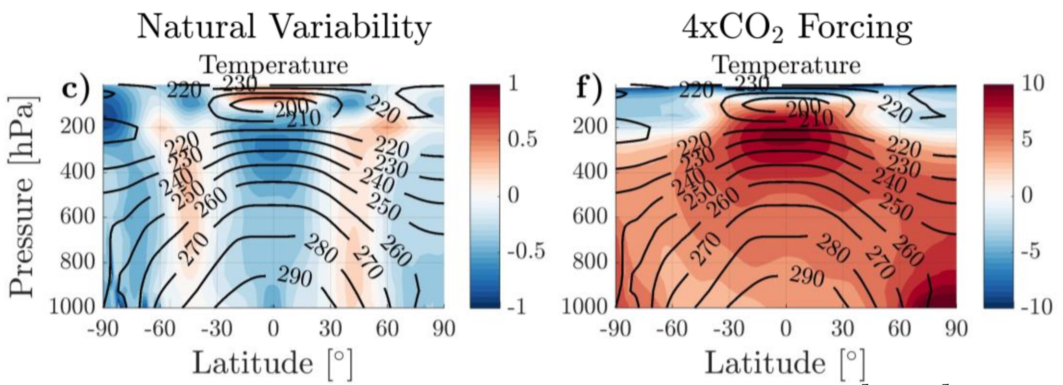
Subtropical jet:
– Shifts poleward
– Strengthens



Menzel et al. 2019

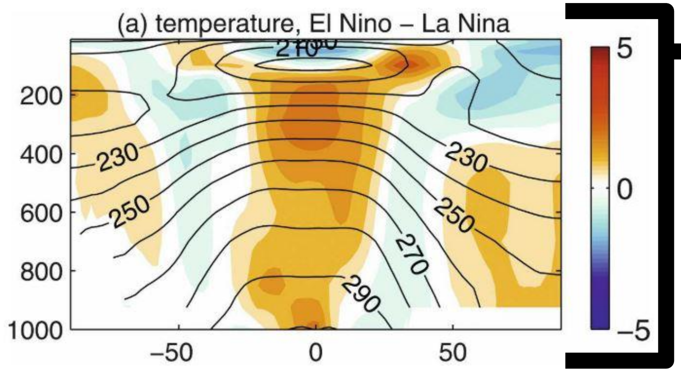
Warming Width

- Lu et al. 2008
- Sun et al. 2014
- Tandon et al. 2014



Menzel et al. 2019

Narrow tropical warming (ENSO)



Lu et al. 2008

more narrow HC

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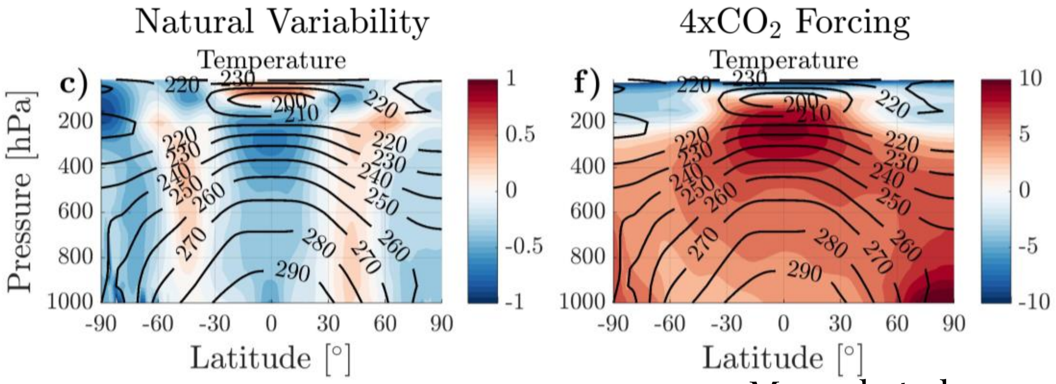

Menzel et al. 2019

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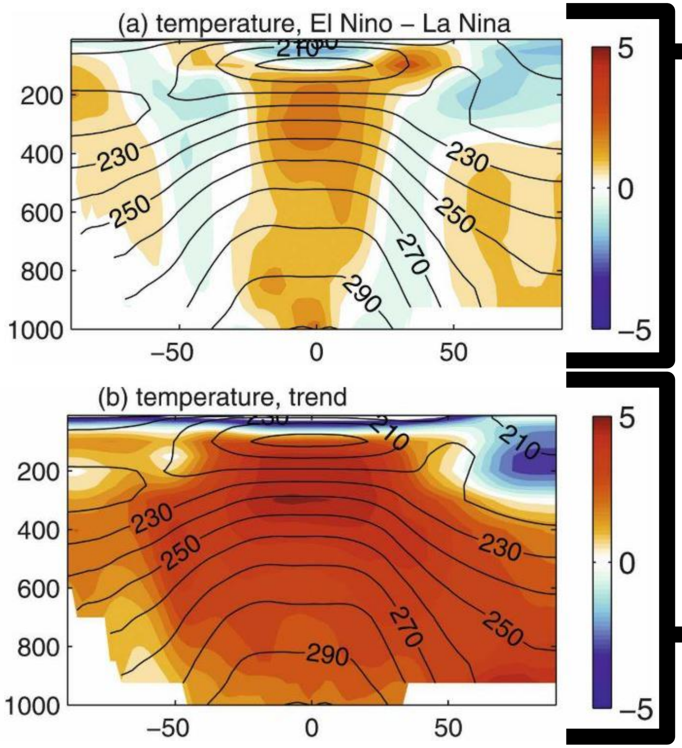

more narrow HC

Broad warming (global forcing)

wider HC

Lu et al. 2008

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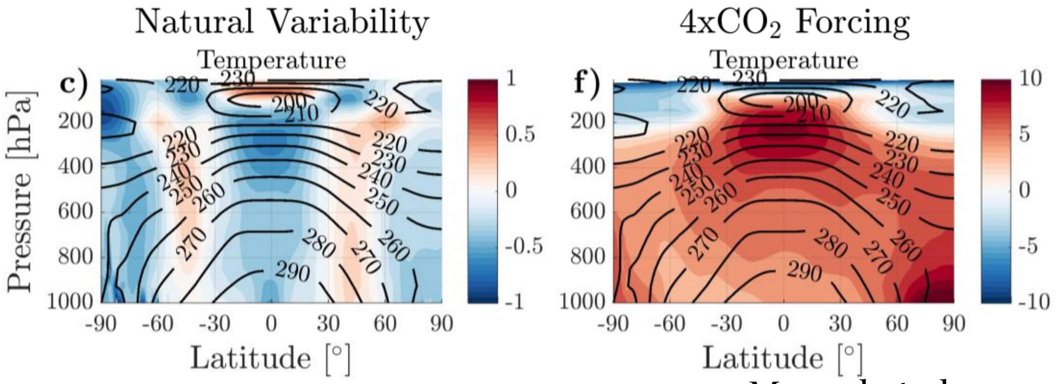

Menzel et al. 2019

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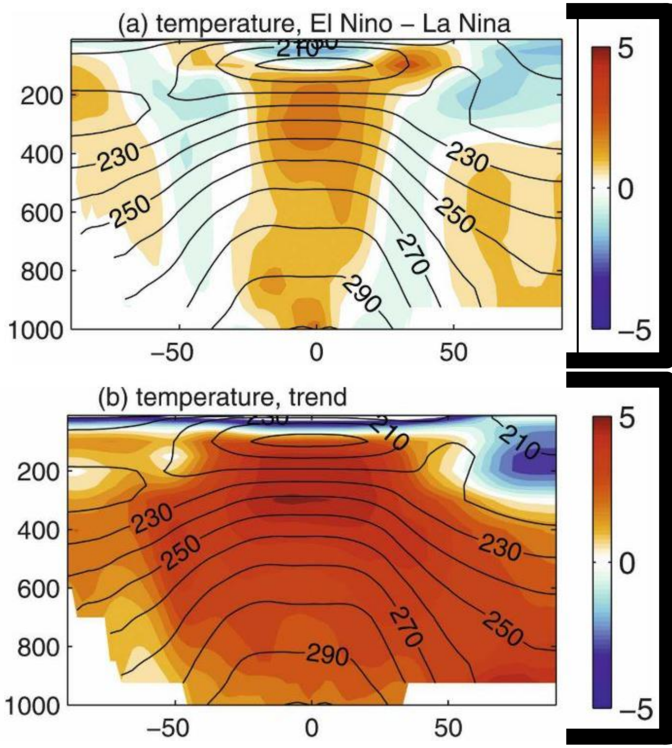
Broad warming (global forcing)



Lu et al. 2008

more narrow HC

stronger STJ

wider HC