Physics of ITCZ width: energetic and dynamical constraints

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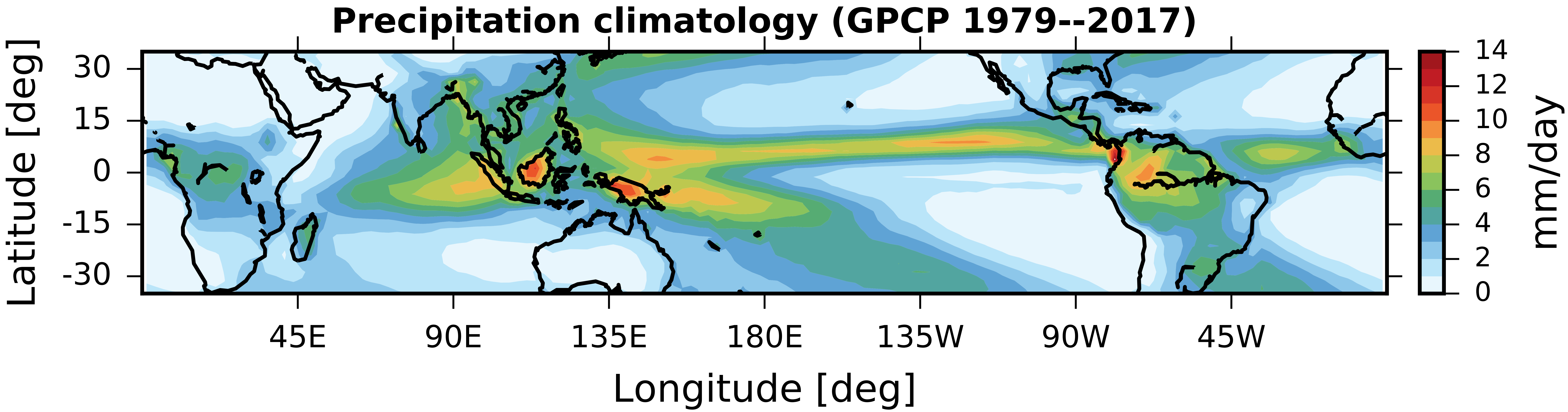
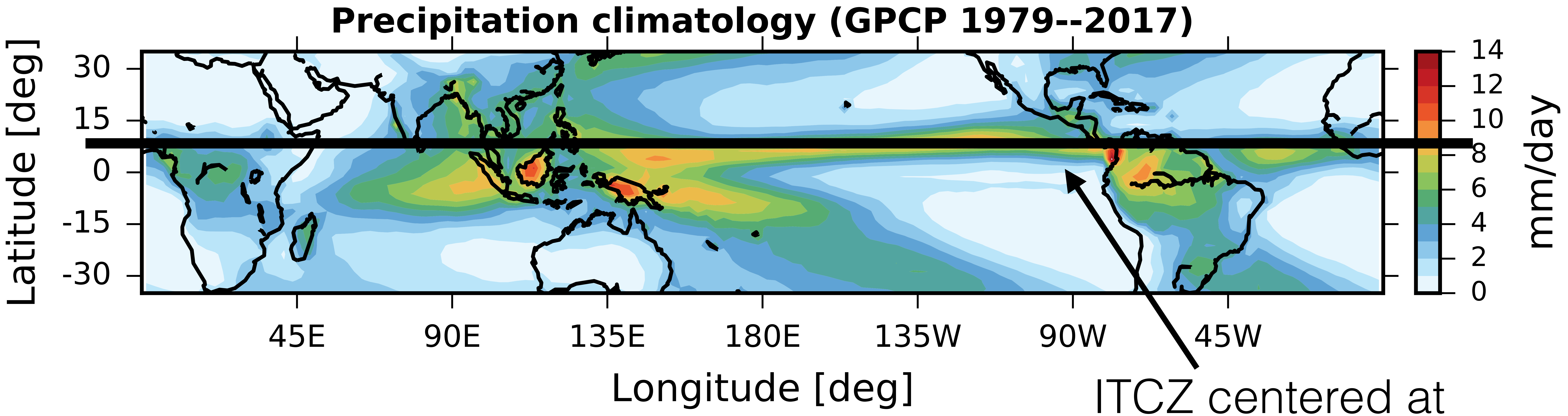
'Physics at the Equator' workshop, ENS de Lyon (Oct 2019)

InterTropical Convergence Zone (ITCZ)

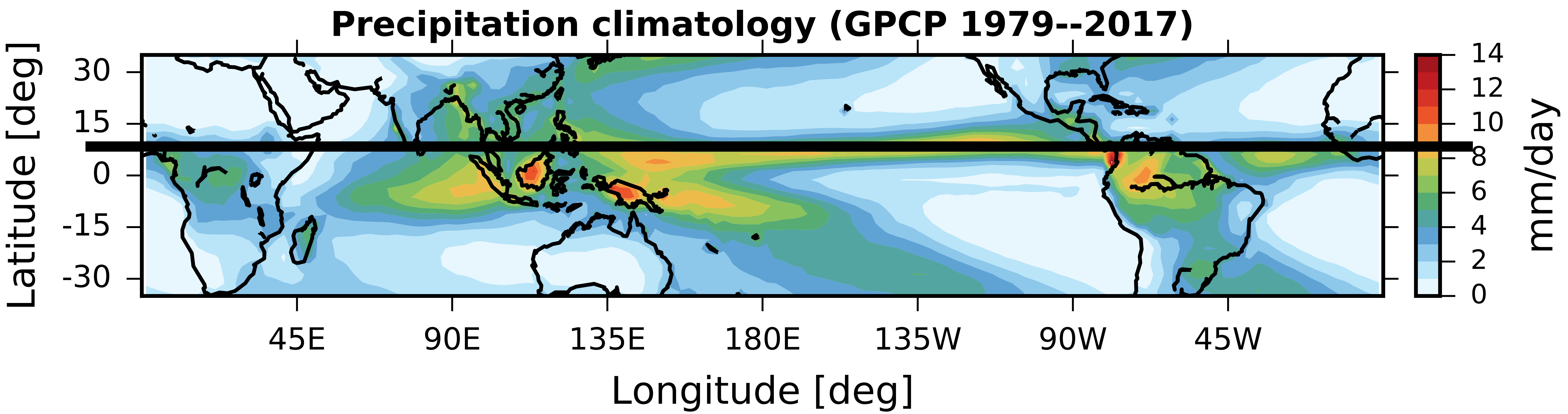


InterTropical Convergence Zone (ITCZ)



ITCZ centered at ~6degN in zonal & annual mean (*e.g. Philander et al 1996*)

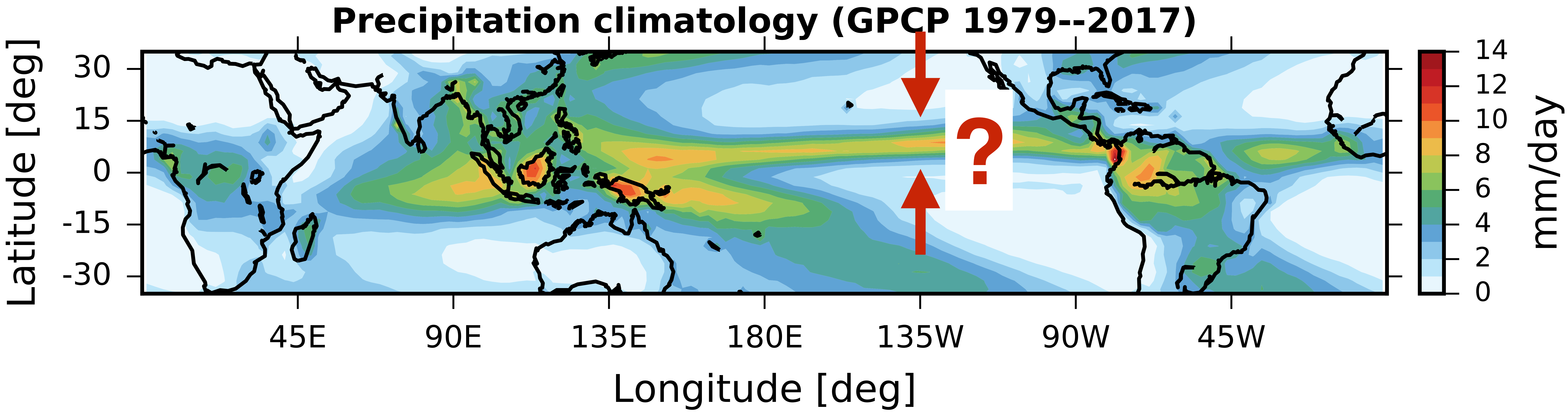
Established energetic theory to understand zonal-mean ITCZ location



ITCZ tends to be in the warmer hemisphere

(e.g., Chiang & Bitz 2005; Broccoli et al 2006; Kang et al 2008; Frierson et al 2013; Donohoe et al 2013; Marshall et al 2014; Bischoff & Schneider 2014; Adam et al 2016; Roberts et al 2017)

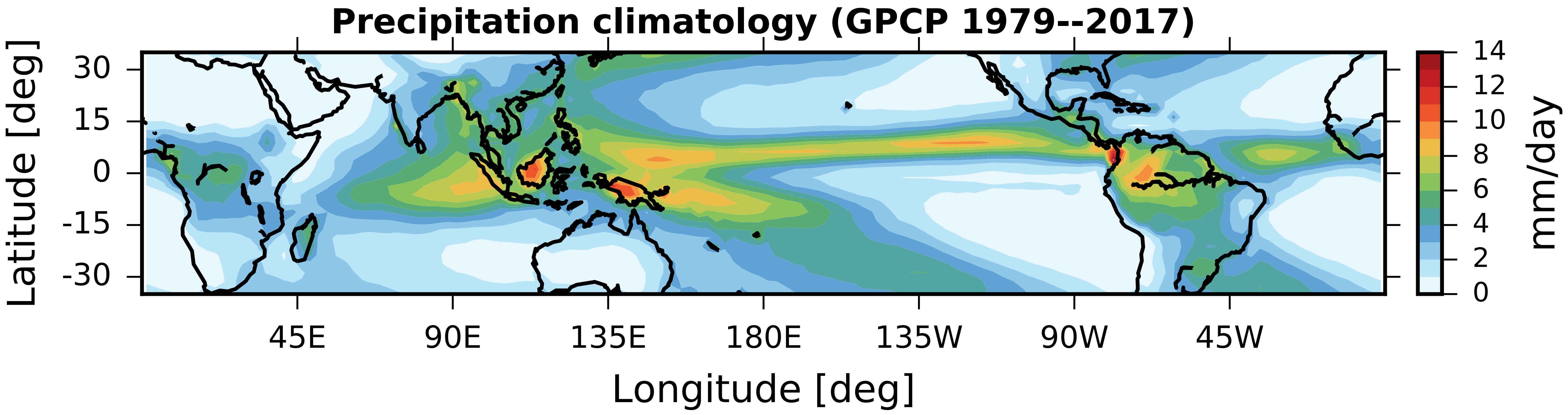
What processes control ITCZ width?



- **ITCZ has narrowed over recent decades** *(Wodzicki & Rapp 2016);* expected to continue narrowing as climate warms *(Byrne et al 2018).* No definitive theory to understand this narrowing

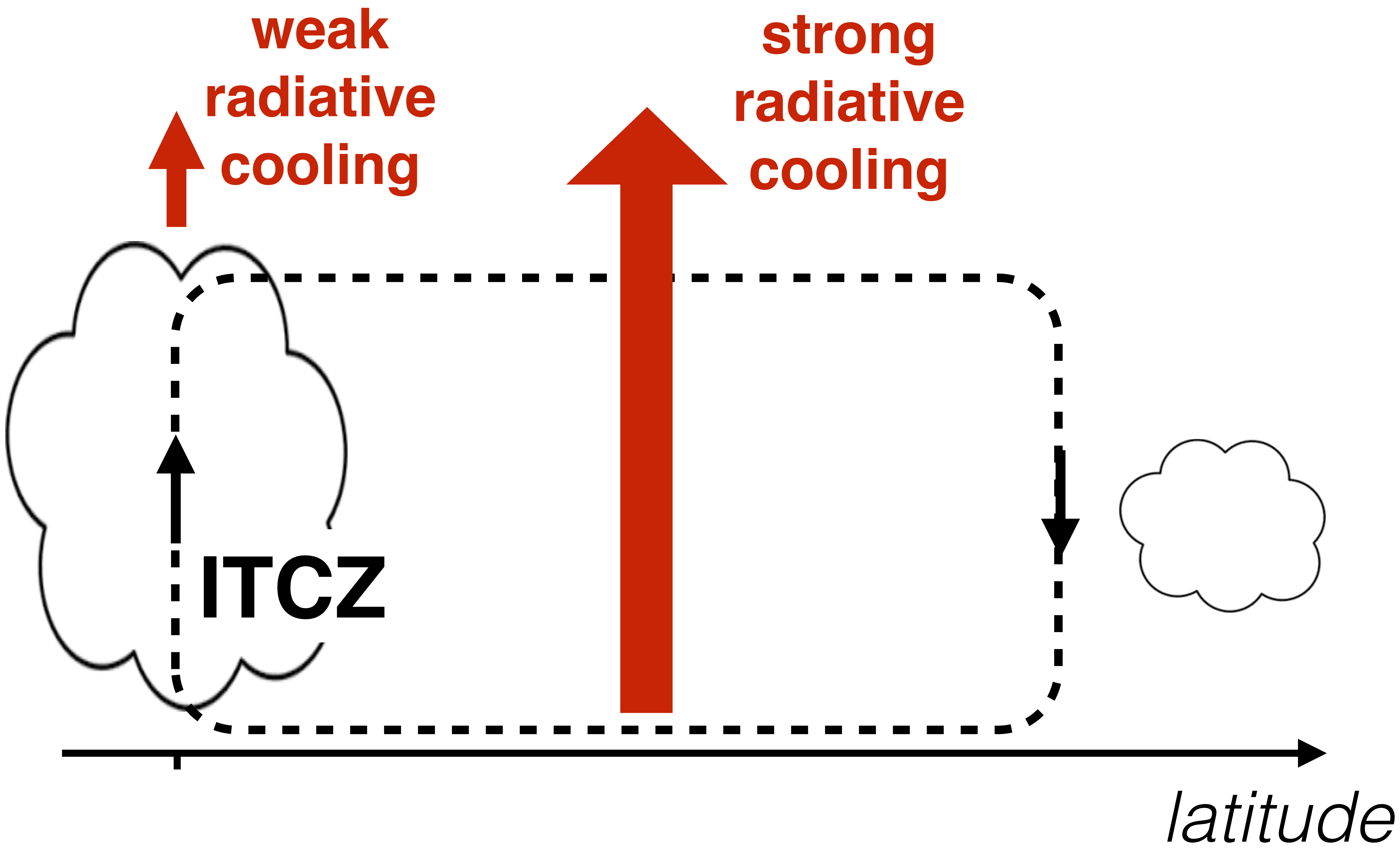
Why is ITCZ width important? Regional climate

- ITCZ width/location controls **regional hydroclimates** in the tropics



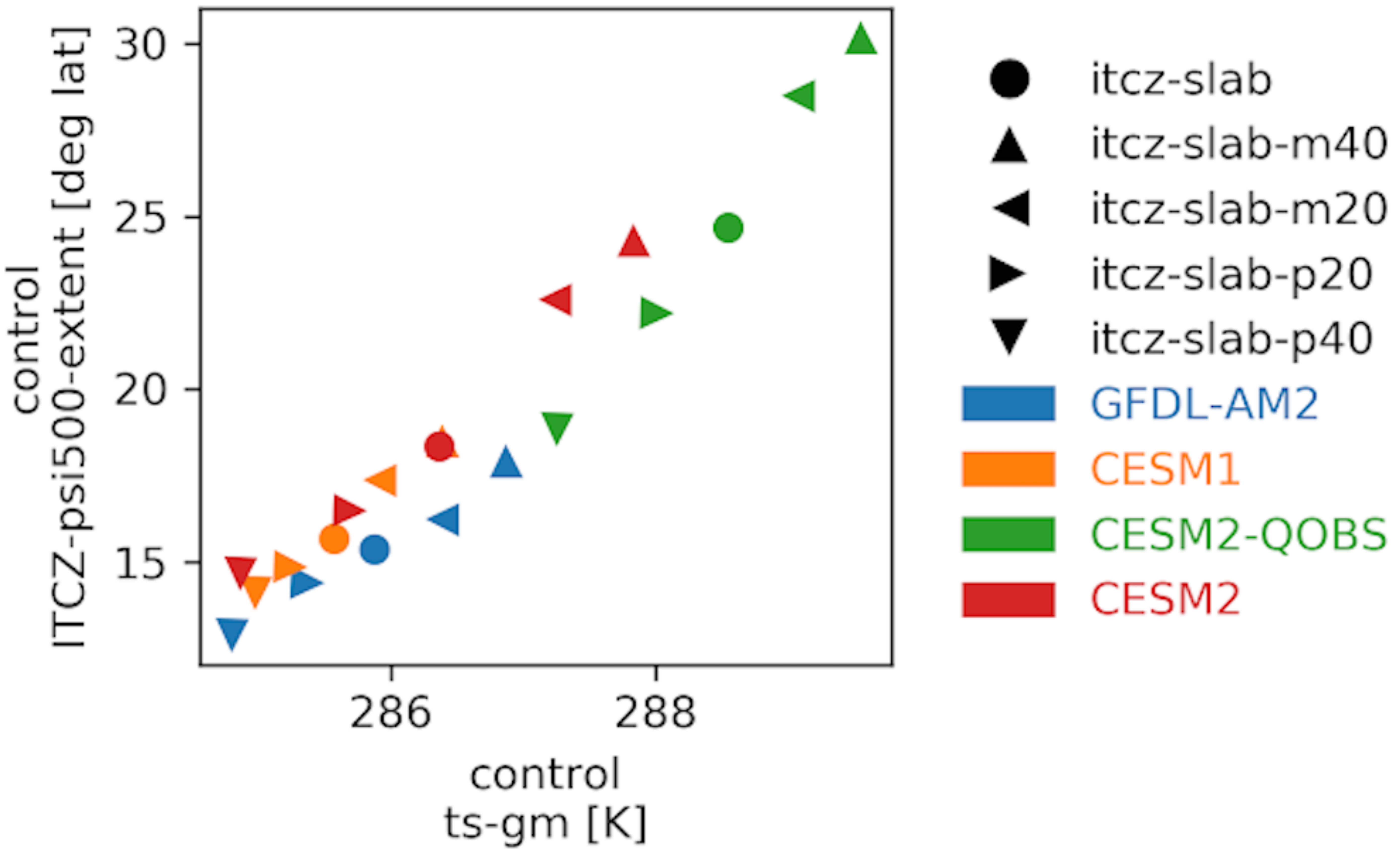
Why is ITCZ width important? Might influence global climate

- ITCZ width/location controls **regional hydroclimates** in the tropics
- ITCZ narrowing or widening potentially important for **global climate sensitivity** via an iris-type feedback (*Pierrehumbert 1995; Bony et al 2016)*



Why is ITCZ width important? Wider ITCZ, warmer climate

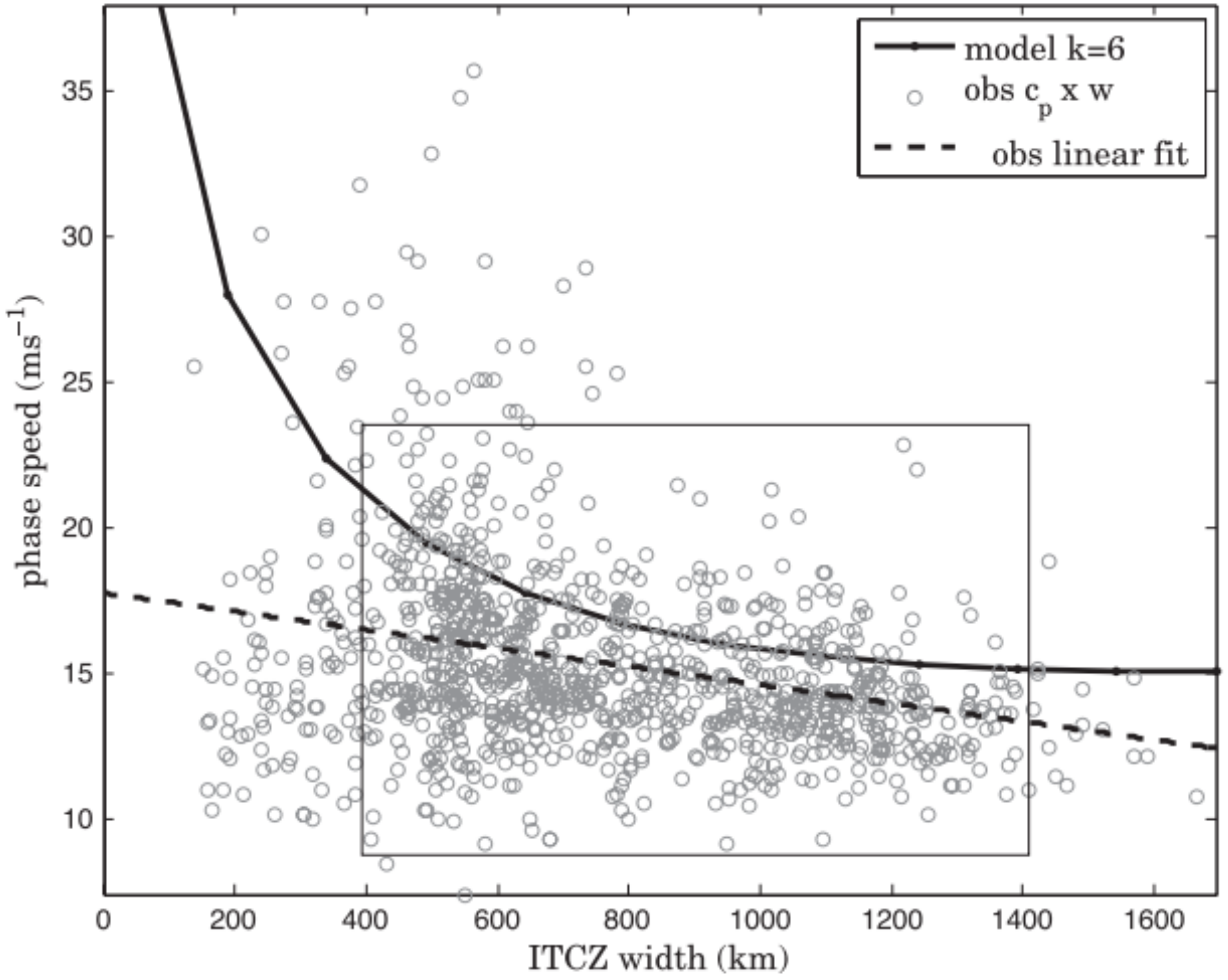
- ITCZ width/location controls **regional hydroclimates** in the tropics
- ITCZ narrowing or widening potentially important for **global climate sensitivity** via an iris-type feedback (*Pierrehumbert 1995; Bony et al 2016)*
- Aquaplanet simulations: **Wider ITCZ, warmer climate —>**



Watt-Meyer, Byrne, Pendergrass, Maher, Webb (in prep)

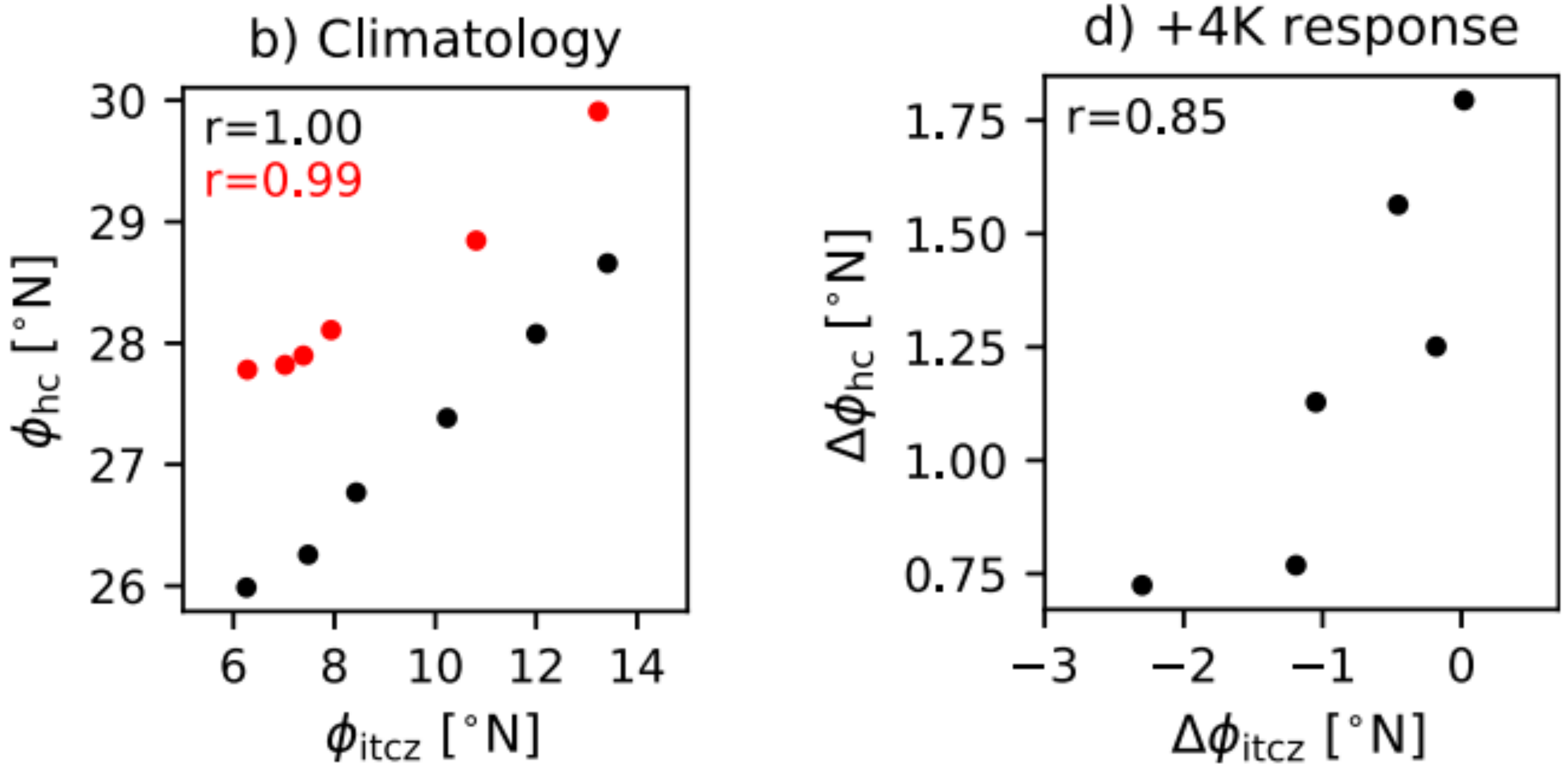
Why is ITCZ width important? Influences tropical waves and Hadley Cell extent

- **ITCZ width modulates tropical waves:** Narrower ITCZ, faster convectively coupled Kelvin waves (*Dias & Pauluis 2011*)



Why is ITCZ width important? Influences tropical waves and Hadley Cell extent

- **ITCZ width modulates tropical waves:** Narrower ITCZ, faster convectively coupled Kelvin waves (*Dias & Pauluis 2011*)
- **ITCZ width influences Hadley Cell extent** + eddy-driven jet position and their responses to warming (*Watt Meyer & Frierson 2019*) —>

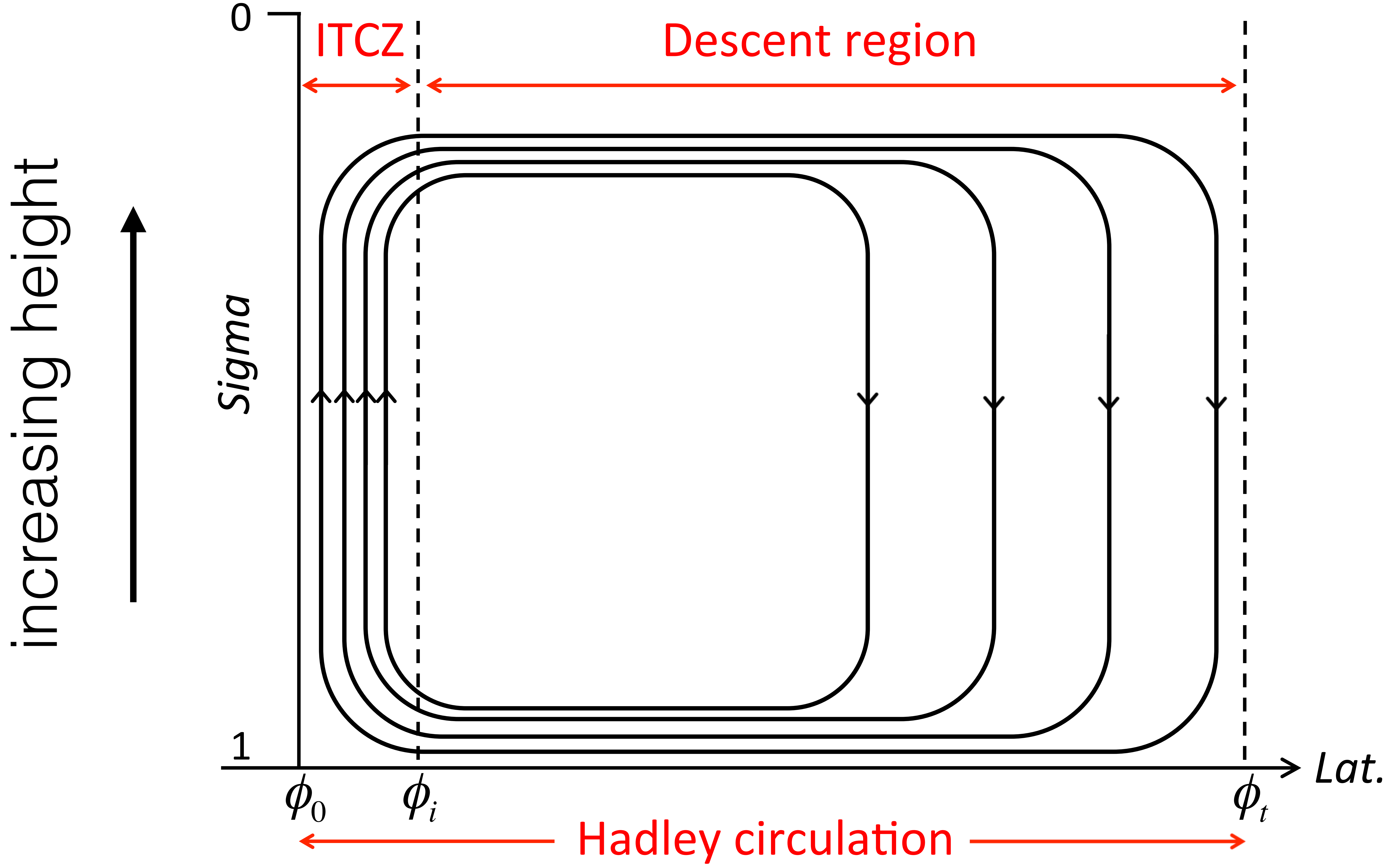


Hadley Cell widening linked to ITCZ narrowing

Outline

- Defining the ITCZ
- Response of zonal-mean ITCZ to global warming in coupled climate models
- Towards understanding the physics controlling ITCZ width
    1. Energetic perspective
    2. Dynamical perspective

Definition of ITCZ width, strength, location: use mid-tropospheric mass streamfunction



Ceppi et al (2013); Byrne & Schneider, J. Climate (2016); Byrne et al, CCCR (2018)

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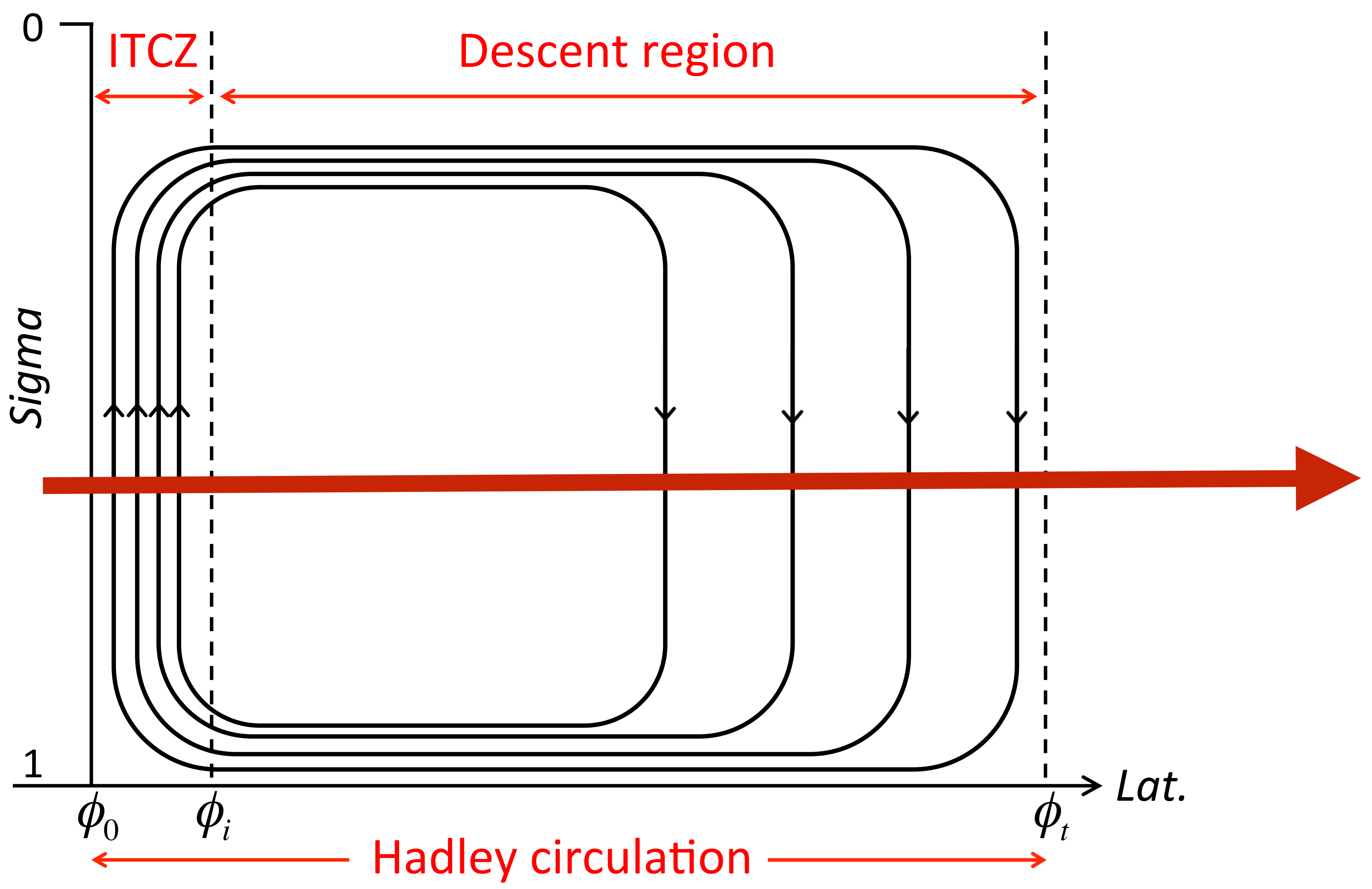
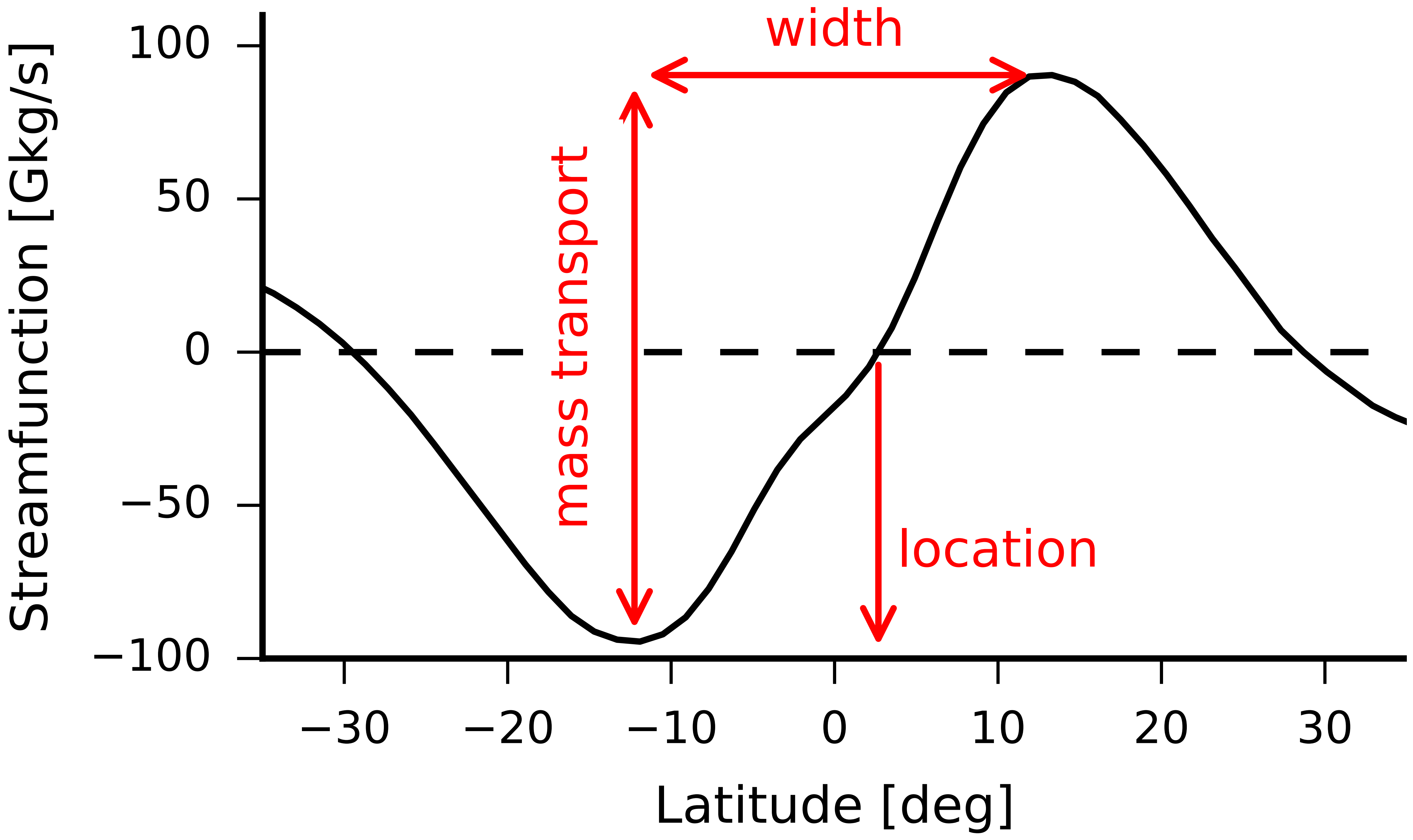




Ceppi et al (2013); Byrne & Schneider, J. Climate (2016); Byrne et al, CCCR (2018)

Definition of ITCZ width, strength, location: use mid-tropospheric mass streamfunction

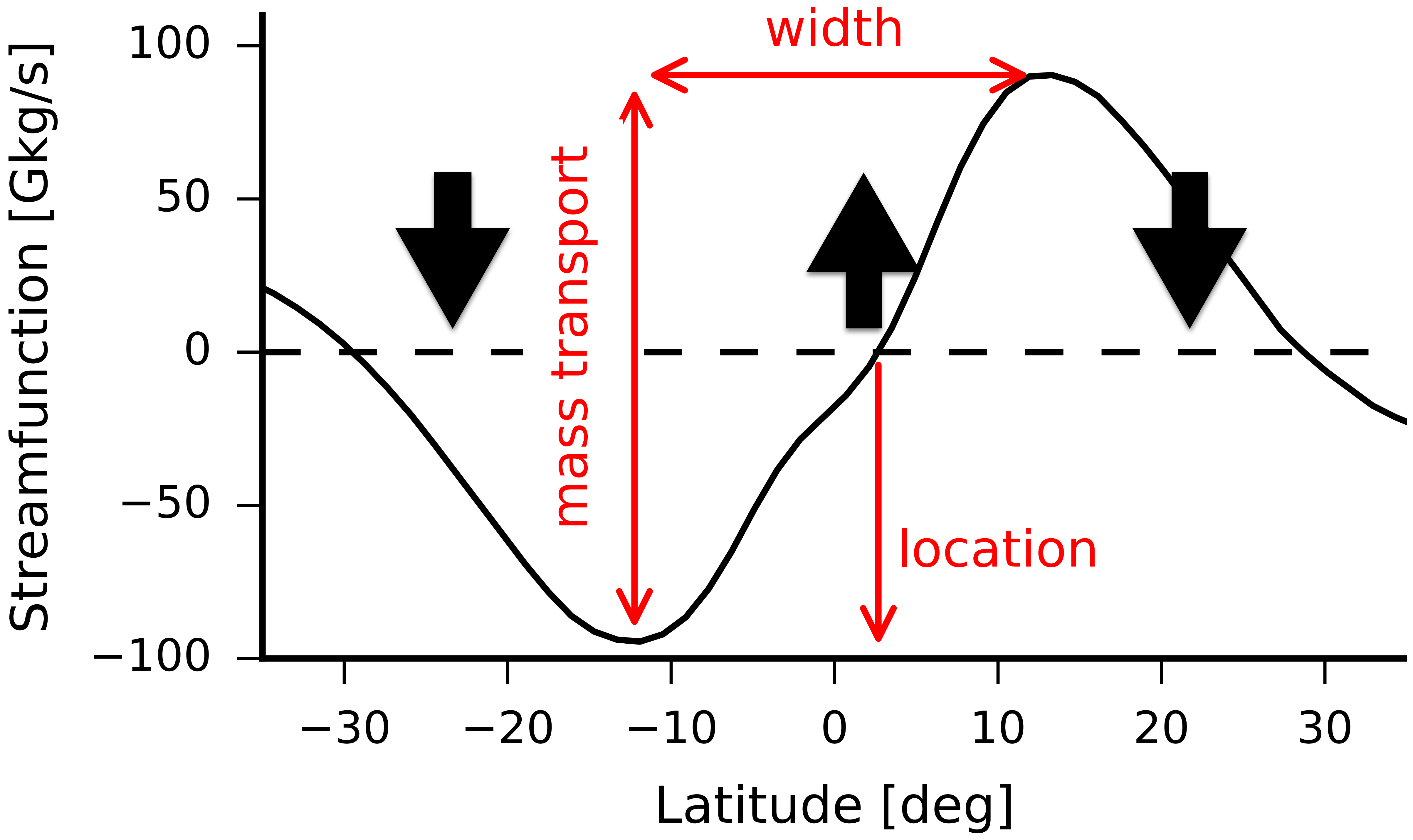
"ITCZ is the tropical region with ascending air"

Width: $$W_{\text{ITCZ}} = \phi|^{N}_{\partial\psi/\partial\phi=0} - \phi|^{S}_{\partial\psi/\partial\phi=0}$$

Strength: $$\omega_{\text{ITCZ}} = -g\frac{\Psi_{\text{ITCZ}}}{A_{\text{ITCZ}}}$$

Location: $$\phi_{\text{ITCZ}} = \phi|_{\psi=0}$$

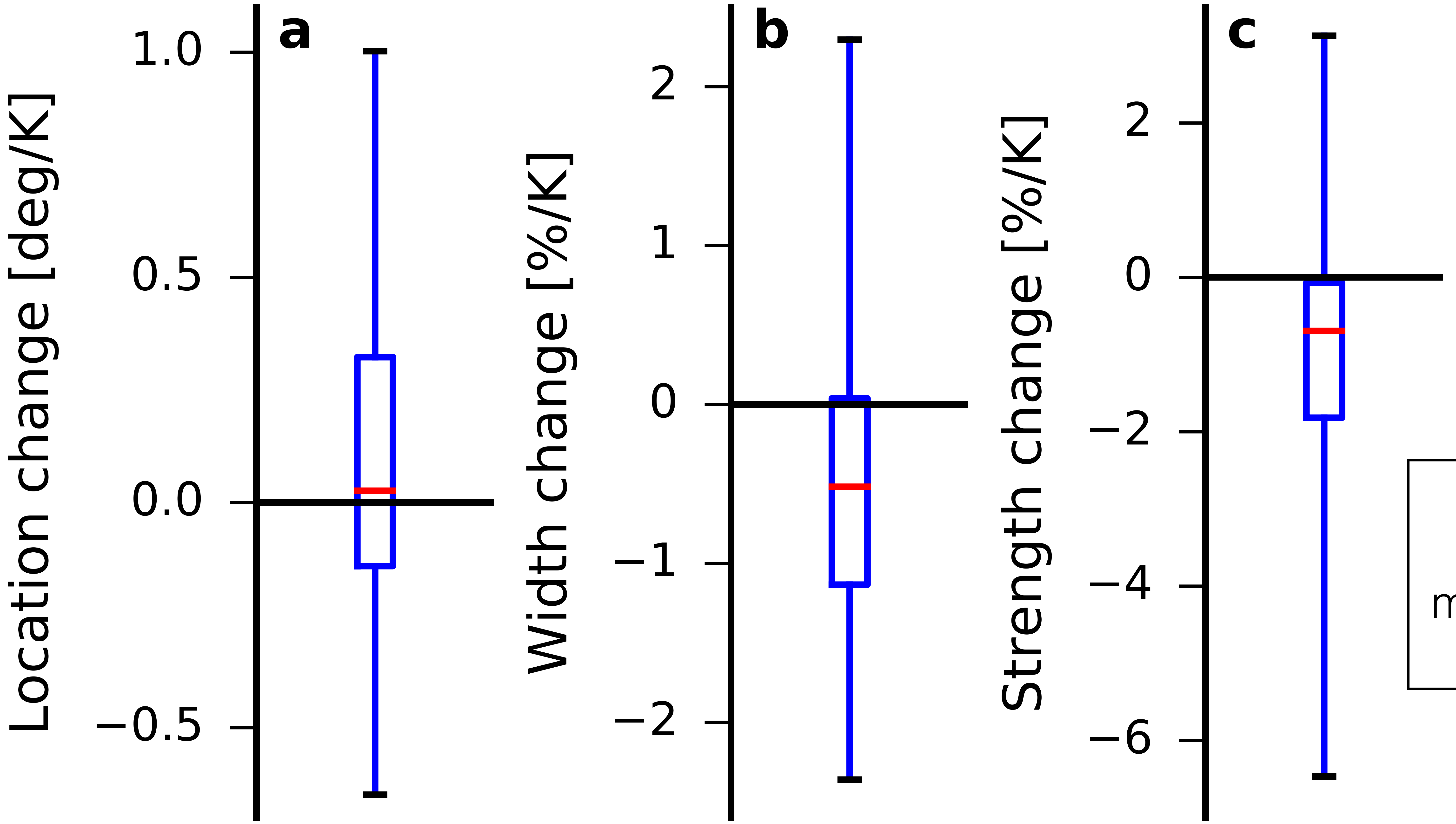
$$\omega \propto -\partial\psi/\partial\phi$$



Ceppi et al (2013); Byrne & Schneider, J. Climate (2016); Byrne et al, CCCR (2018)

How does the ITCZ structure respond to global warming? CMIP5 (=old-ish IPCC) models

No robust change in ITCZ location, but ~75% of models show narrowing and weakening with warming



32 CMIP5 models: RCP8.5 (2079–2098) minus historical (1985–2004)

Byrne et al, CCCR (2018)

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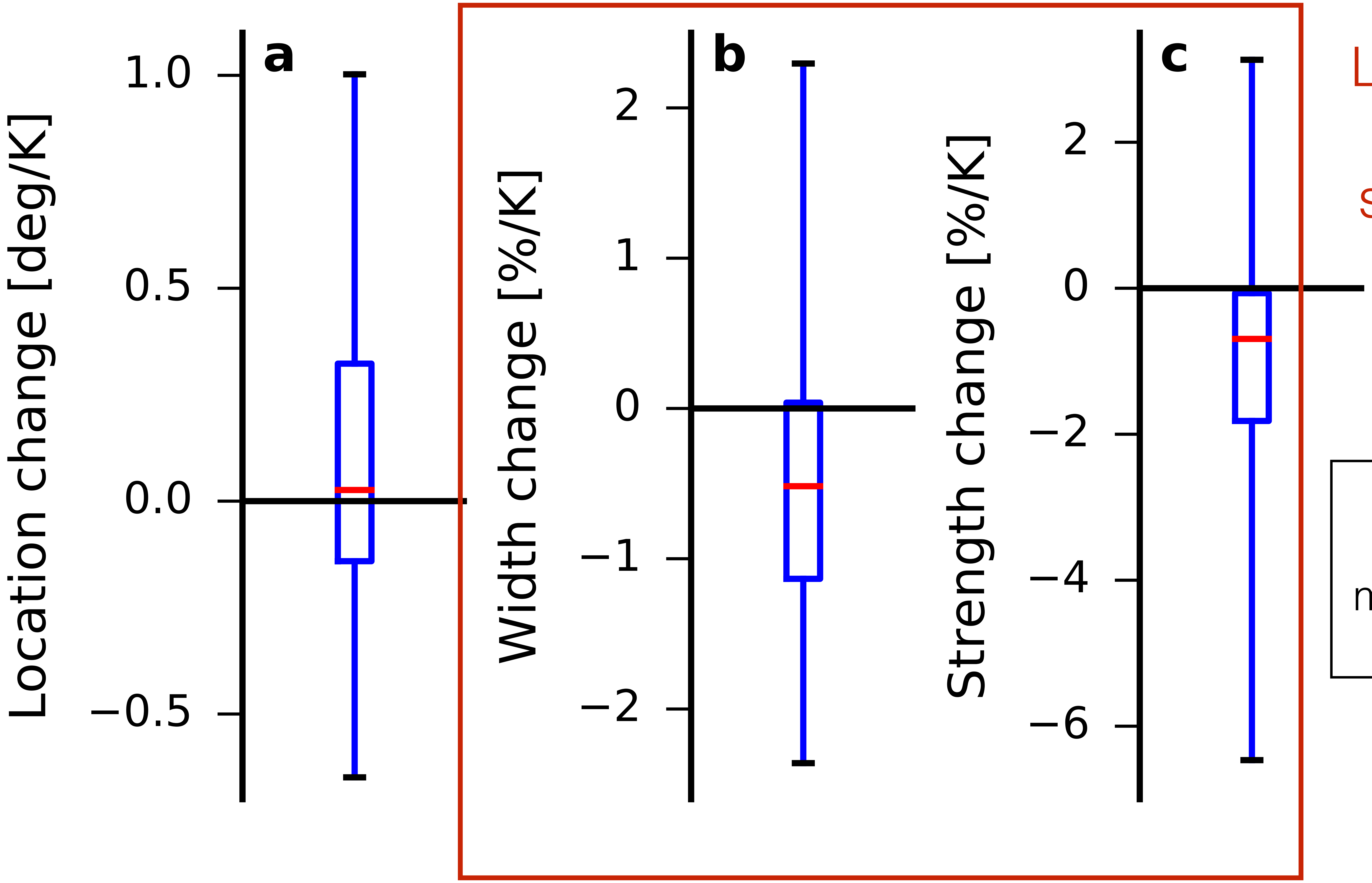
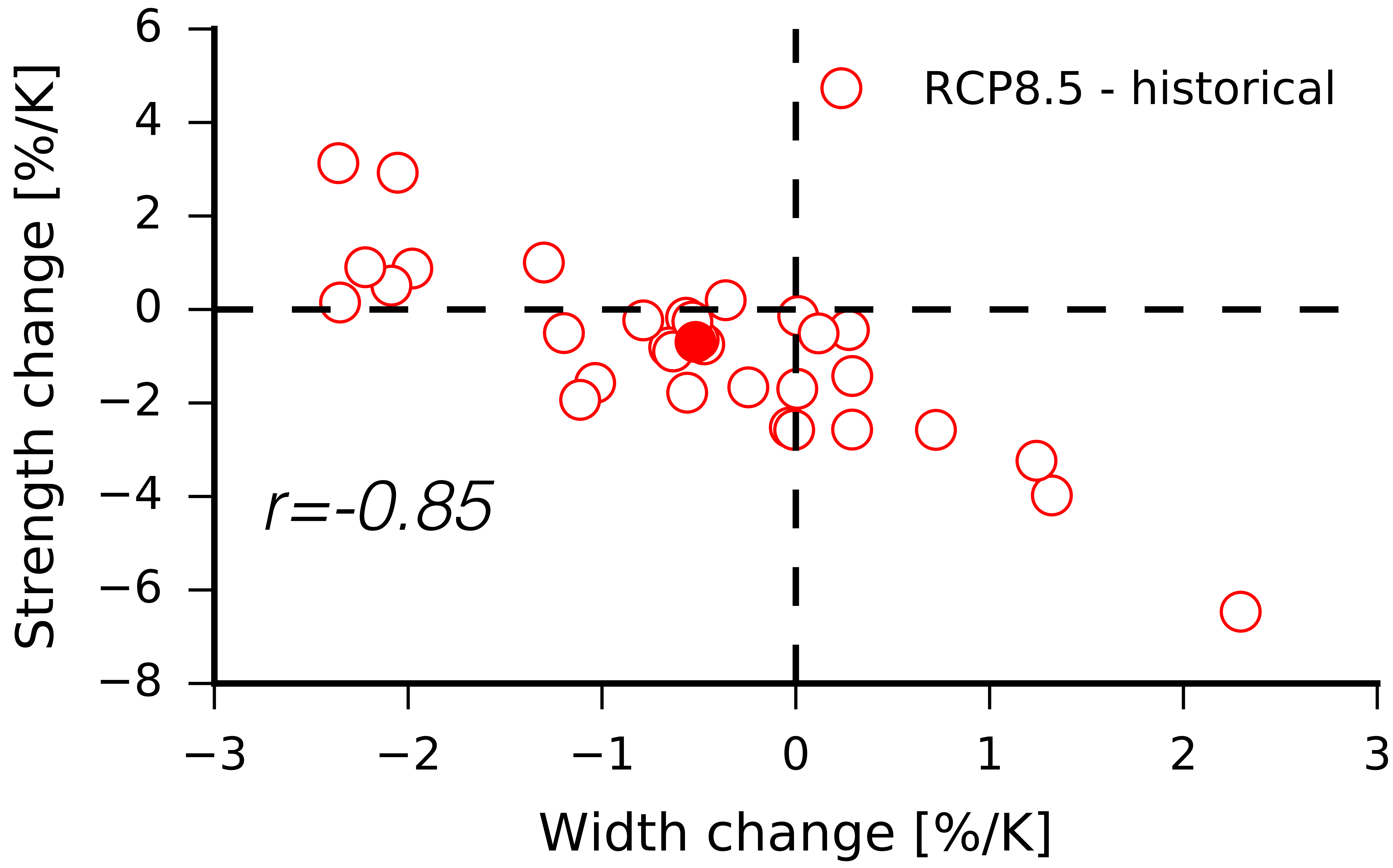


Look more closely at width and strength changes

32 CMIP5 models: RCP8.5 (2079–2098) minus historical (1985–2004)

Byrne et al, CCCR (2018)

Strong relationship between changes in ITCZ width and strength



Byrne et al, CCCR (2018)

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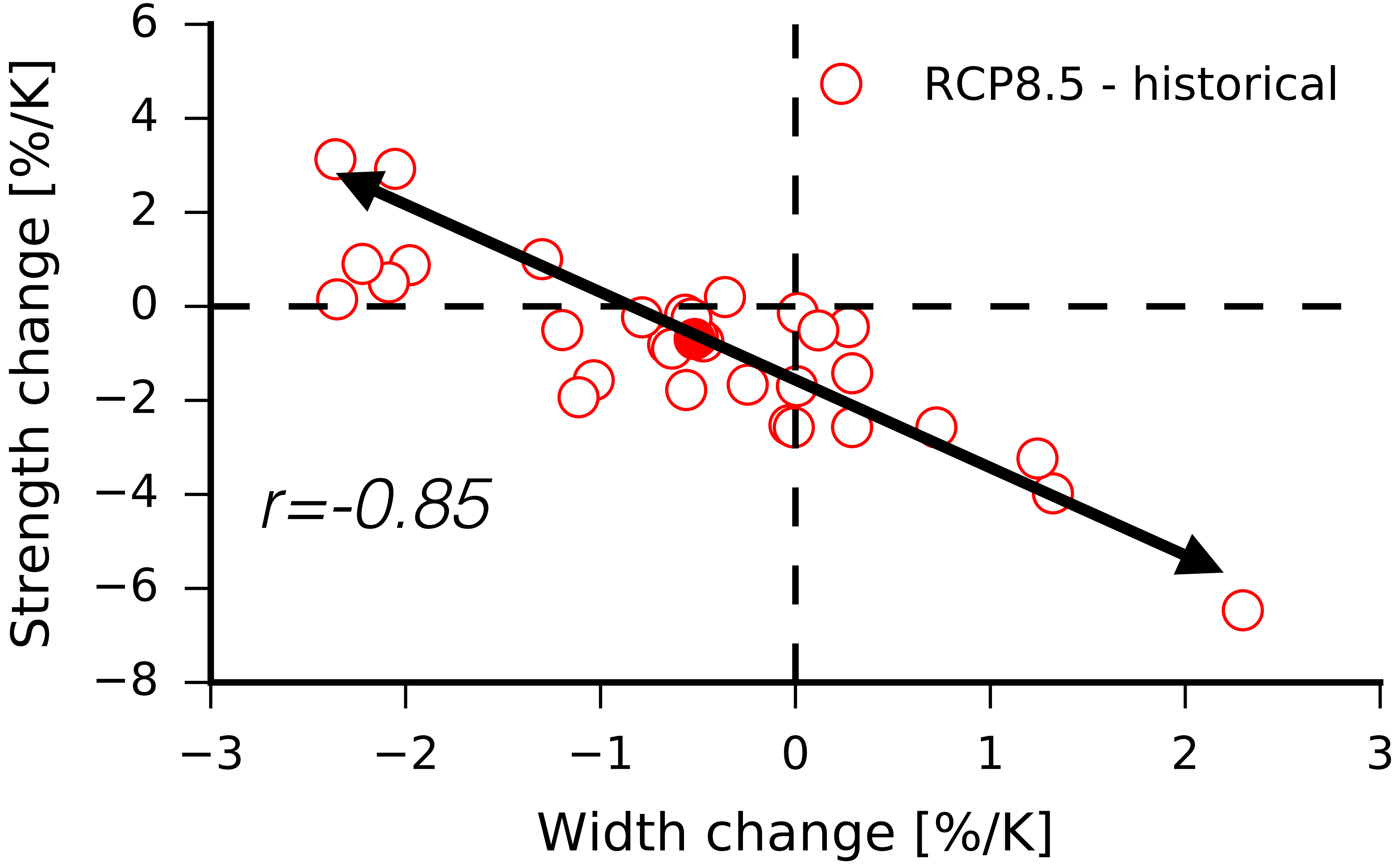

Relationship not fully understood... But if we understand ITCZ width, should give insights into ITCZ strength

Byrne et al, CCCR (2018)

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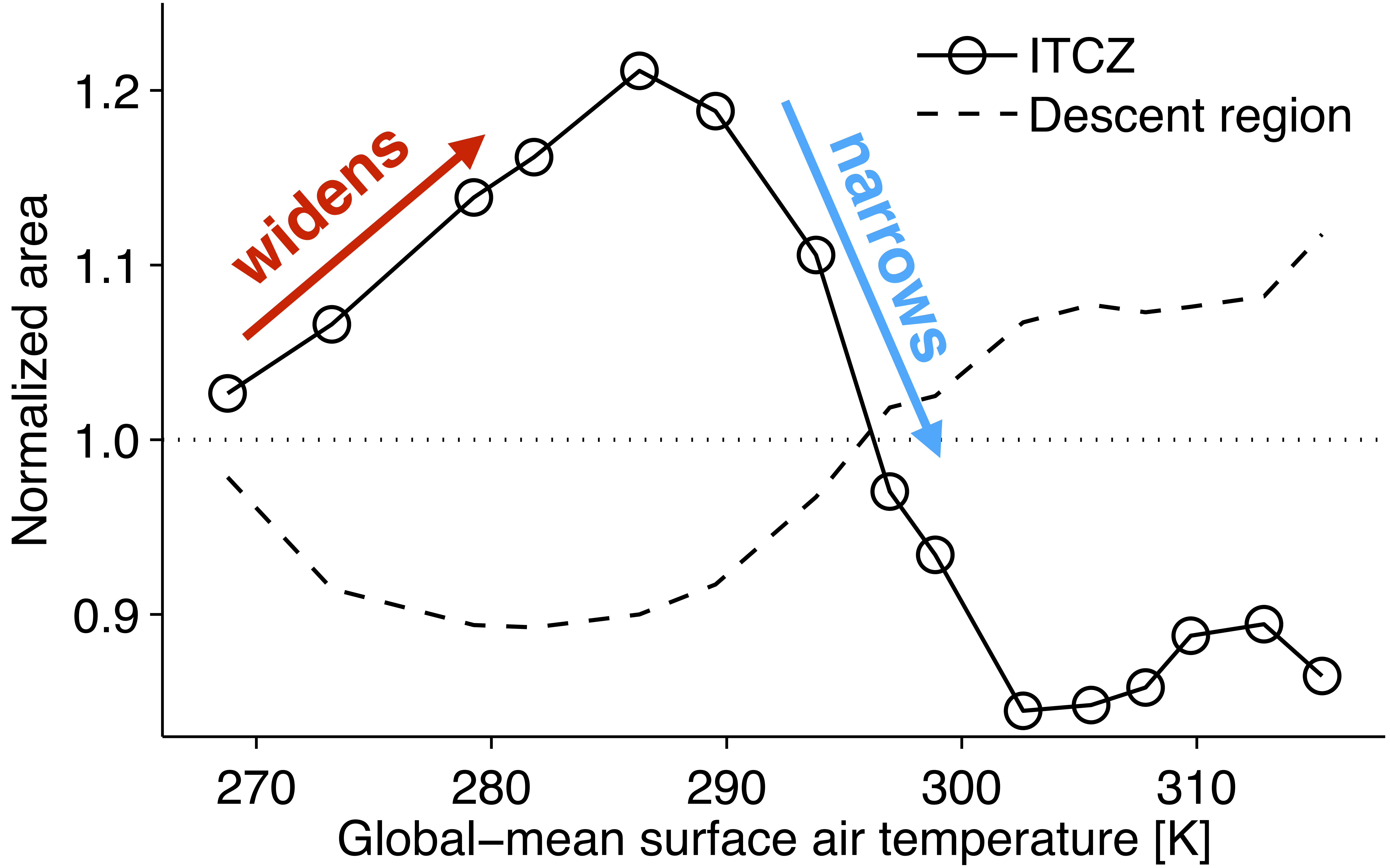
Idealised GCM simulations

- Moist, idealised GCM, slab-ocean aquaplanet *(Frierson et al 2006; Frierson 2007; O'Gorman & Schneider 2008)*
- Perpetual equinox, specified longwave optical thickness
- "Moist" = latent heating and a water cycle only; no cloud-radiative or water vapour-radiative feedbacks
- **Simulate a wide range of climates** (270K – 305K) by re-scaling longwave optical thickness (~varying CO_2)

Byrne & Schneider, J. Climate (2016)

ITCZ sometimes widens, sometimes narrows with warming



Byrne & Schneider, J. Climate (2016)

Energetic perspective to understand ITCZ width and its sensitivity to climate

Objective: Derive physically-based expressions for the ITCZ width and its sensitivity to changes in climate

Method: Use mass and moist static energy budgets of the Hadley cell

Byrne & Schneider, J. Climate (2016). See also Sobel & Neelin (2006) and Popp & Silvers (2017) for different energetic approaches to this problem.

Energetic perspective to understand ITCZ width and its sensitivity to climate

Hadley cell mass budget:

$$A_{\mathrm{itcz}}\omega_{\mathrm{itcz}} = -A_{\mathrm{desc}}\omega_{\mathrm{desc}}$$

$$\Rightarrow \frac{A_{\mathrm{itcz}}}{A_{\mathrm{desc}}} = -\frac{\omega_{\mathrm{desc}}}{\omega_{\mathrm{itcz}}}$$

"what goes up in the ITCZ must come down in the descent region"

Byrne & Schneider, J. Climate (2016)

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Atmospheric energy budget:

$$\overline{S} - \overline{L} - \overline{O} = \nabla \cdot \{\overline{vh}\}$$

net energy input ("NEI")

Total moist static energy (MSE) divergence by the atmosphere

$[h \equiv c_p T + L_v q + gz]$

Byrne & Schneider, J. Climate (2016)

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Atmospheric energy budget:

$$\overline{S} - \overline{L} - \overline{O}$$

$$= -\Delta h\omega/g + \{\overline{v}\cdot\nabla\overline{h}\} + \{\nabla\cdot\overline{v'h'}\}$$

Mean divergent flow ($-\Delta h\omega/g$)

Mean advection ($\{\overline{v}\cdot\nabla\overline{h}\}$)

Transient eddies ($\{\nabla\cdot\overline{v'h'}\}$)

Byrne & Schneider, J. Climate (2016)

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Atmospheric energy budget:

$$\overline{S} - \overline{L} - \overline{O}$$

$$= -\boxed{\Delta h}\omega/g + \{\overline{v}\cdot\nabla\overline{h}\} + \{\nabla\cdot\overline{v'h'}\}$$

Gross moist stability (GMS)
~ *h(top) - h(bottom)*

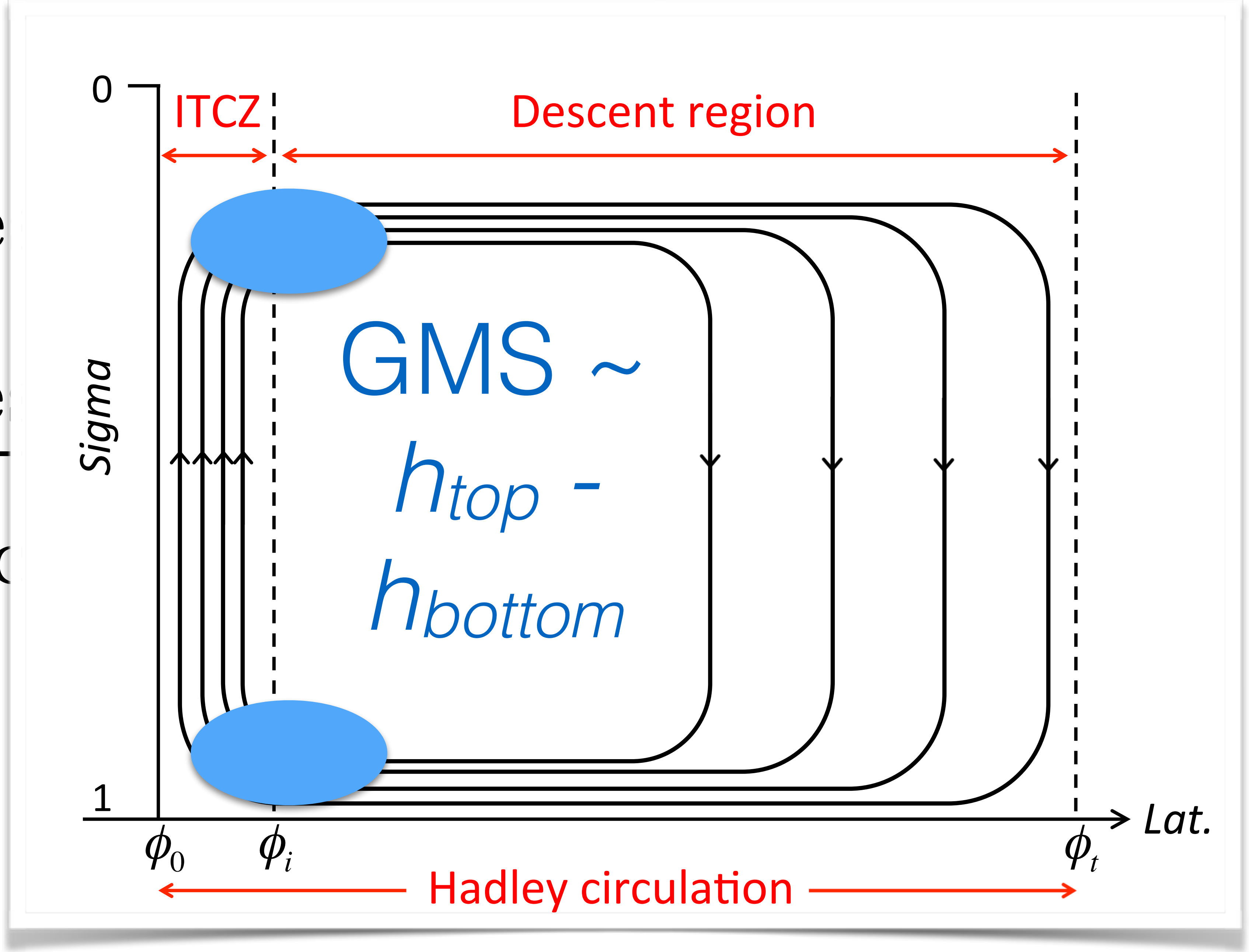
Byrne & Schneider, J. Climate (2016)

Energetic perspective to understand ITCZ width and its sensitivity to climate

Hadley cell mass budget:

$$A_{\mathrm{itcz}}\omega_{\mathrm{itcz}} = -A_{\mathrm{de}}$$

$$\Rightarrow \frac{A_{\mathrm{itcz}}}{A_{\mathrm{desc}}} = -\frac{\omega_{\mathrm{de}}}{\omega_{\mathrm{itc}}}$$



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~ *h(top) - h(bottom)*

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Energetic perspective to understand ITCZ width and its sensitivity to climate

Hadley cell mass budget + **Atmospheric energy budget** →

$$\frac{A_{\mathrm{itcz}}}{A_{\mathrm{desc}}} = -\frac{\omega_{\mathrm{desc}}}{\omega_{\mathrm{itcz}}}$$

$$= -\frac{\langle \overline{S} - \overline{L} - \overline{O} - \{\overline{v} \cdot \nabla \overline{h}\} - \{\nabla \cdot \overline{v'h'}\}\rangle_{\mathrm{desc}}}{\langle \overline{S} - \overline{L} - \overline{O} - \{\overline{v} \cdot \nabla \overline{h}\} - \{\nabla \cdot \overline{v'h'}\}\rangle_{\mathrm{itcz}}} \frac{\Delta h_{\mathrm{itcz}}}{\Delta h_{\mathrm{desc}}}$$

Byrne & Schneider, J. Climate (2016)

Energetic perspective to understand ITCZ width and its sensitivity to climate

Hadley cell mass budget + **Atmospheric energy budget** ⟶

$$\frac{A_{\text{itcz}}}{A_{\text{desc}}} = -\frac{\omega_{\text{desc}}}{\omega_{\text{itcz}}}$$

$$= -\frac{\langle \overline{S} - \overline{L} - \overline{O} - \{\overline{v}\cdot\nabla\overline{h}\} - \{\nabla\cdot\overline{v'h'}\}\rangle_{\text{desc}}}{\langle \overline{S} - \overline{L} - \overline{O} - \{\overline{v}\cdot\nabla\overline{h}\} - \{\nabla\cdot\overline{v'h'}\}\rangle_{\text{itcz}}} \frac{\Delta h_{\text{itcz}}}{\Delta h_{\text{desc}}}$$

< 1

Descent region more stable than ITCZ —> expect narrow ITCZ relative to descent region (all else equal)

Byrne & Schneider, J. Climate (2016)

Expression for sensitivity of the ITCZ width to climate change: depends on gross moist stability, TOA and SFC fluxes, poleward energy transport

$$\frac{\delta A_{\mathrm{itcz}}}{A_{\mathrm{itcz}}} - \frac{\delta A_{\mathrm{desc}}}{A_{\mathrm{desc}}} =$$

gross moist stability → $\delta\mathrm{GMS}+$

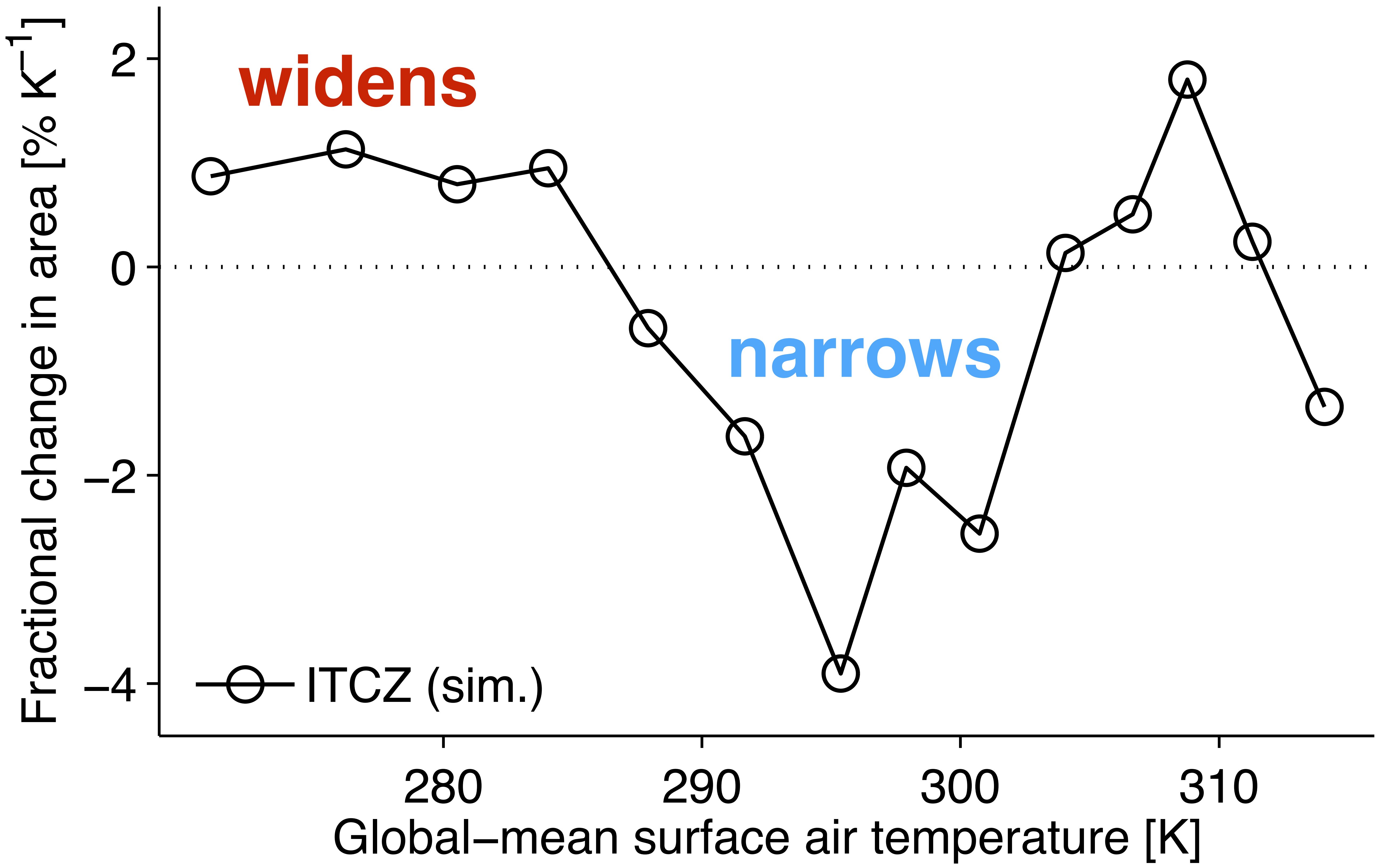
$\delta\mathrm{NEI}+$ ← net energy input to the atmosphere (TOA and SFC fluxes)

mean moist static energy advection → $\delta\mathrm{MeanAdv}+$

$\delta\mathrm{Eddy}$ ← transient-eddy moist static energy divergence

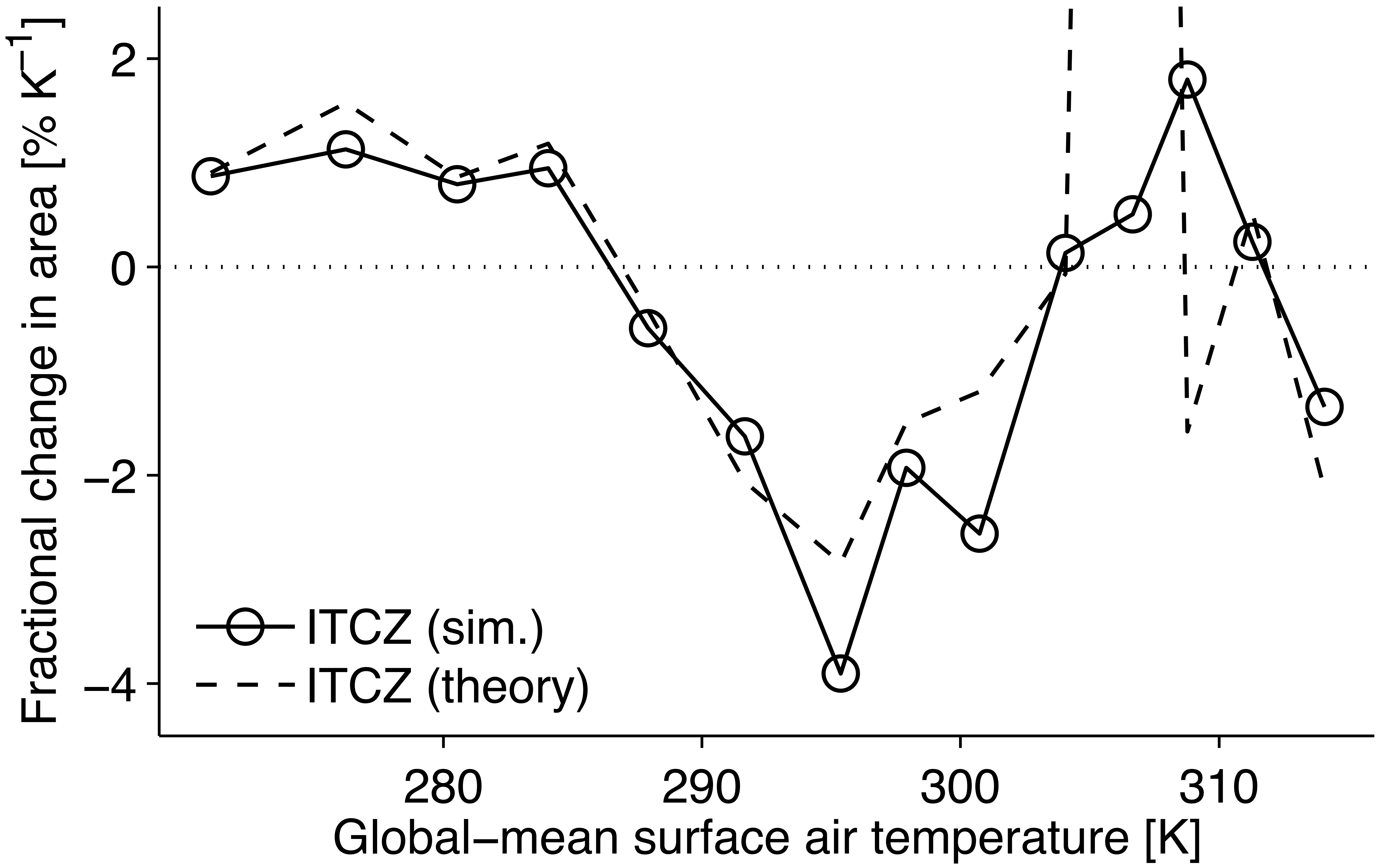
Byrne & Schneider, J. Climate (2016). See also Sobel & Neelin (2006) and Popp & Silvers (2017) for different energetic approaches to this problem.

Apply energetic perspective to understand ITCZ width changes in idealised GCM



Byrne & Schneider, J. Climate (2016)

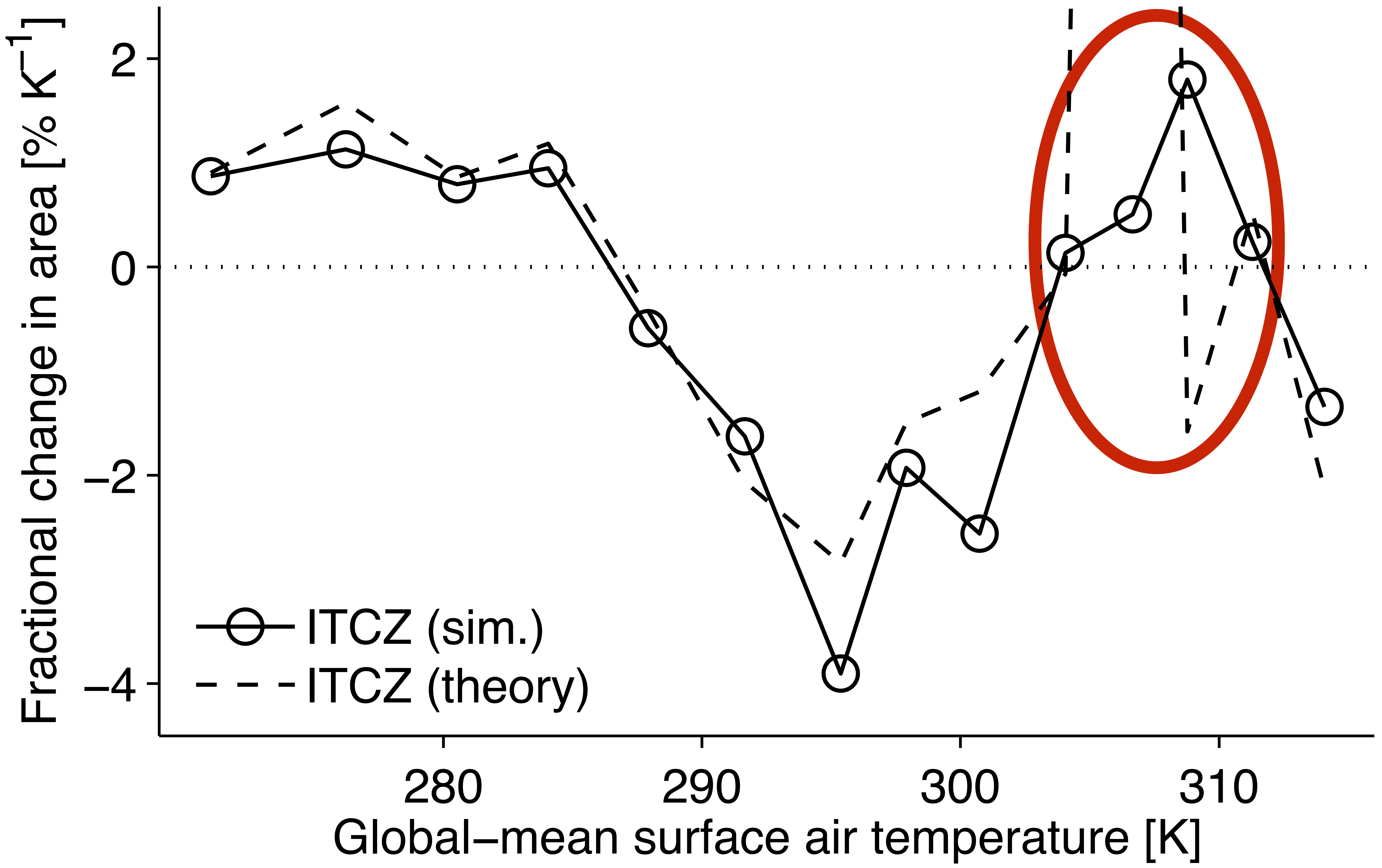
Energetic perspective mostly captures fractional changes in ITCZ width



$$\frac{\delta A_{\mathrm{itcz}}}{A_{\mathrm{itcz}}} - \frac{\delta A_{\mathrm{desc}}}{A_{\mathrm{desc}}} = \delta\mathrm{GMS} + \delta\mathrm{NEI} + \delta\mathrm{MeanAdv} + \delta\mathrm{Eddy}$$

Byrne & Schneider, J. Climate (2016)

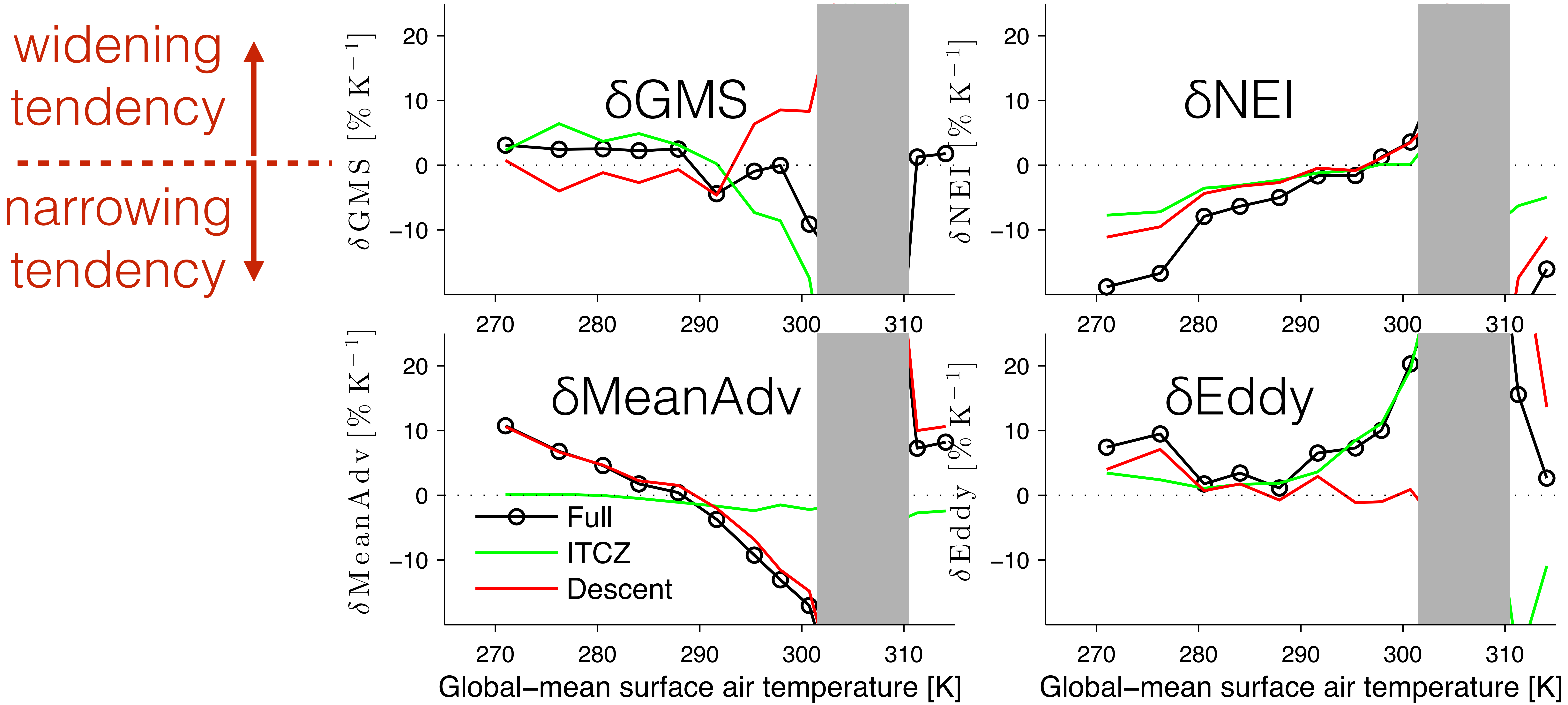
Energetic perspective mostly captures fractional changes in ITCZ width



GMS passes through zero, scaling blows up!

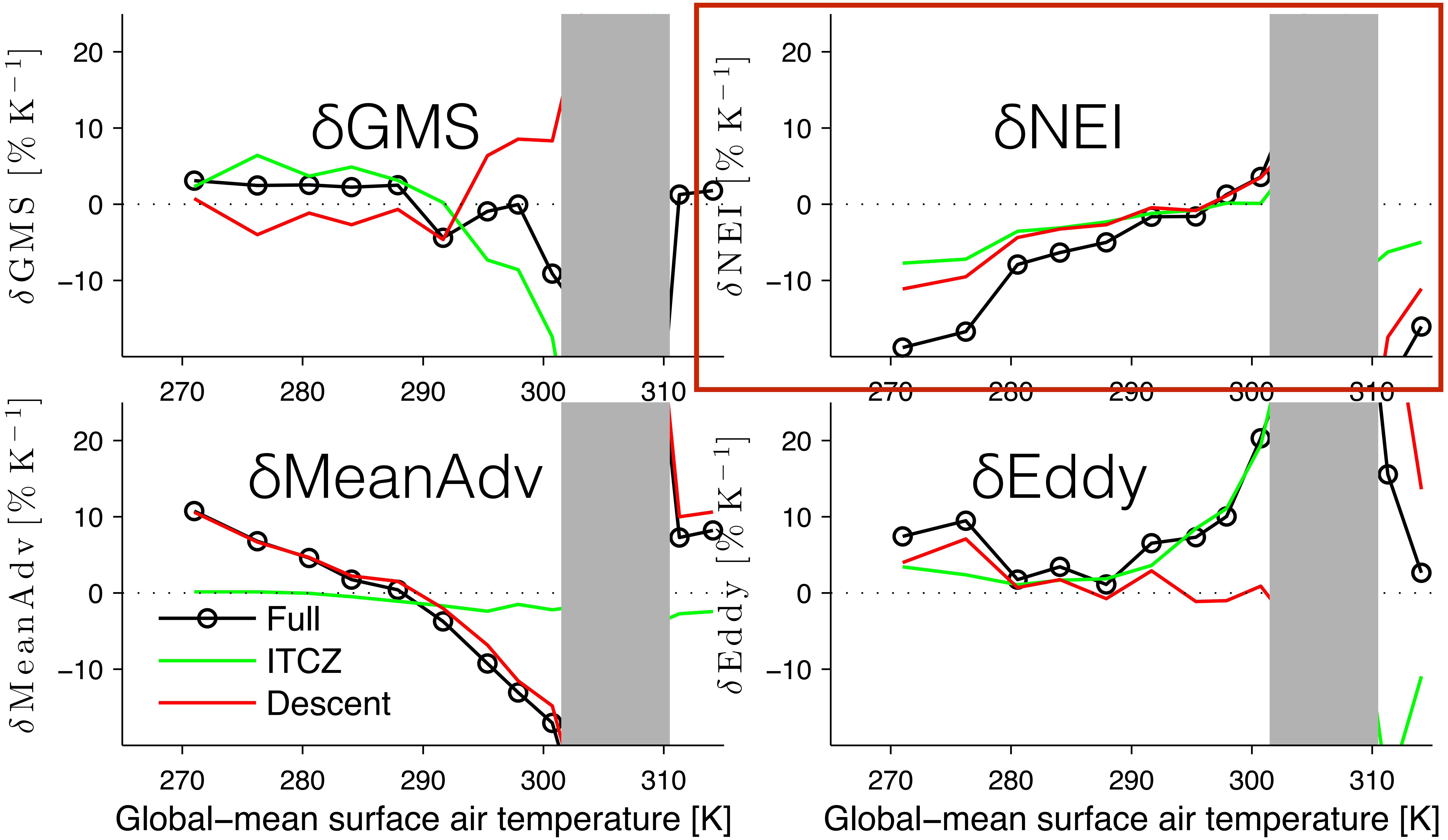
Byrne & Schneider, J. Climate (2016)

Decompose the processes that influence ITCZ width: Four contributions



Byrne & Schneider, J. Climate (2016)

Why do increases in net energy input to the tropical atmosphere with global warming narrow the ITCZ?



Physical intuition for why increases in energy input to atmosphere narrow ITCZ?

Byrne & Schneider, J. Climate (2016)

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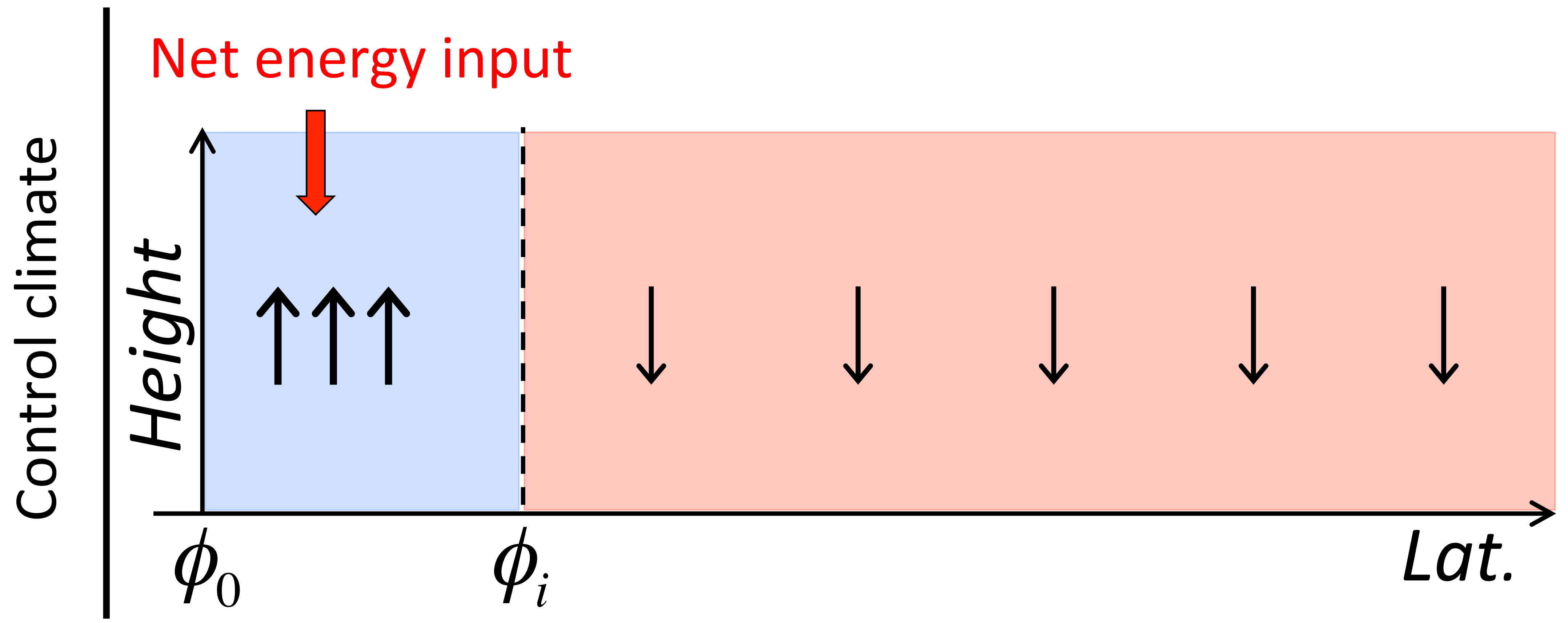

Hadley cell mass budget

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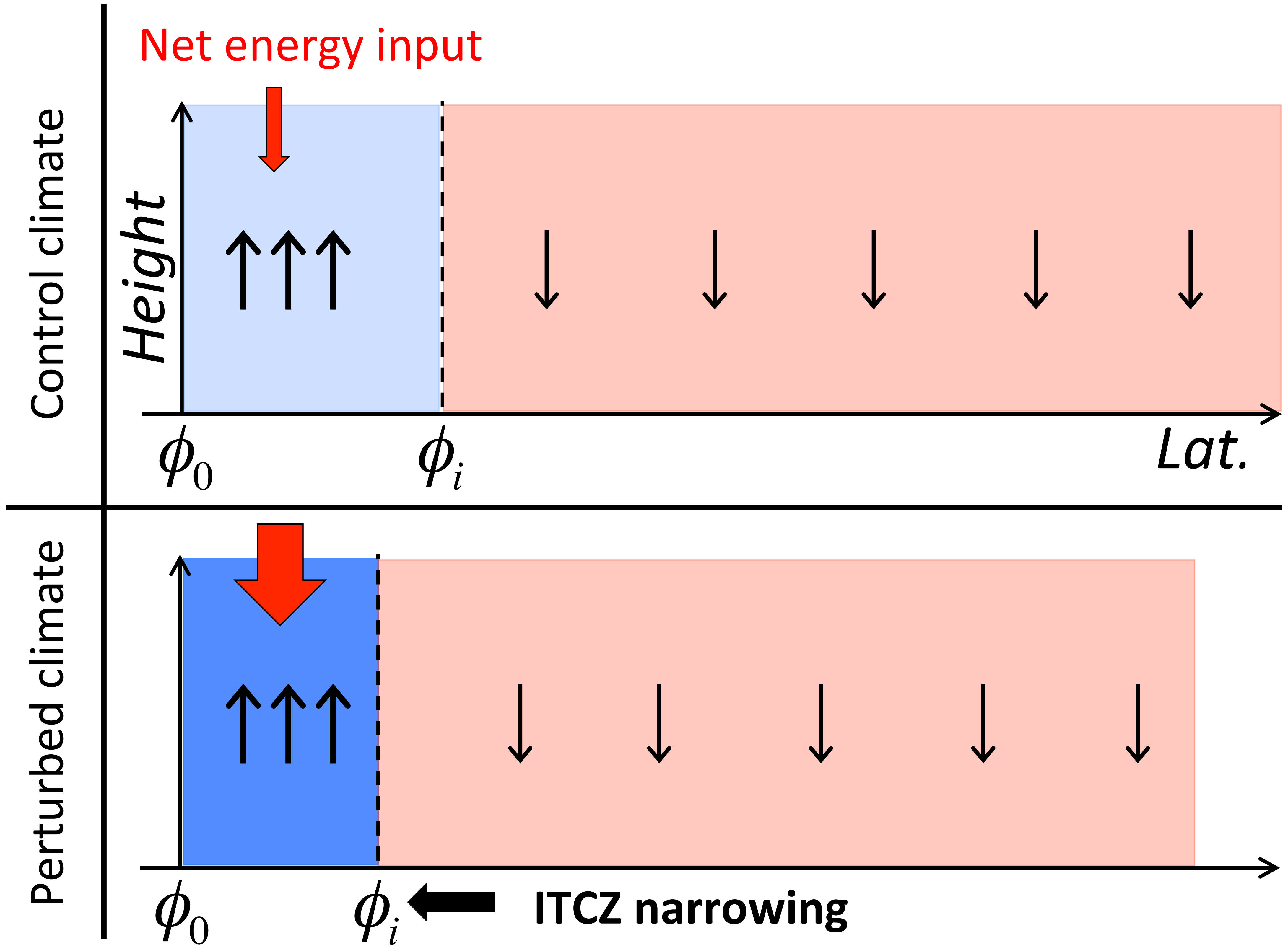

Hadley cell mass budget

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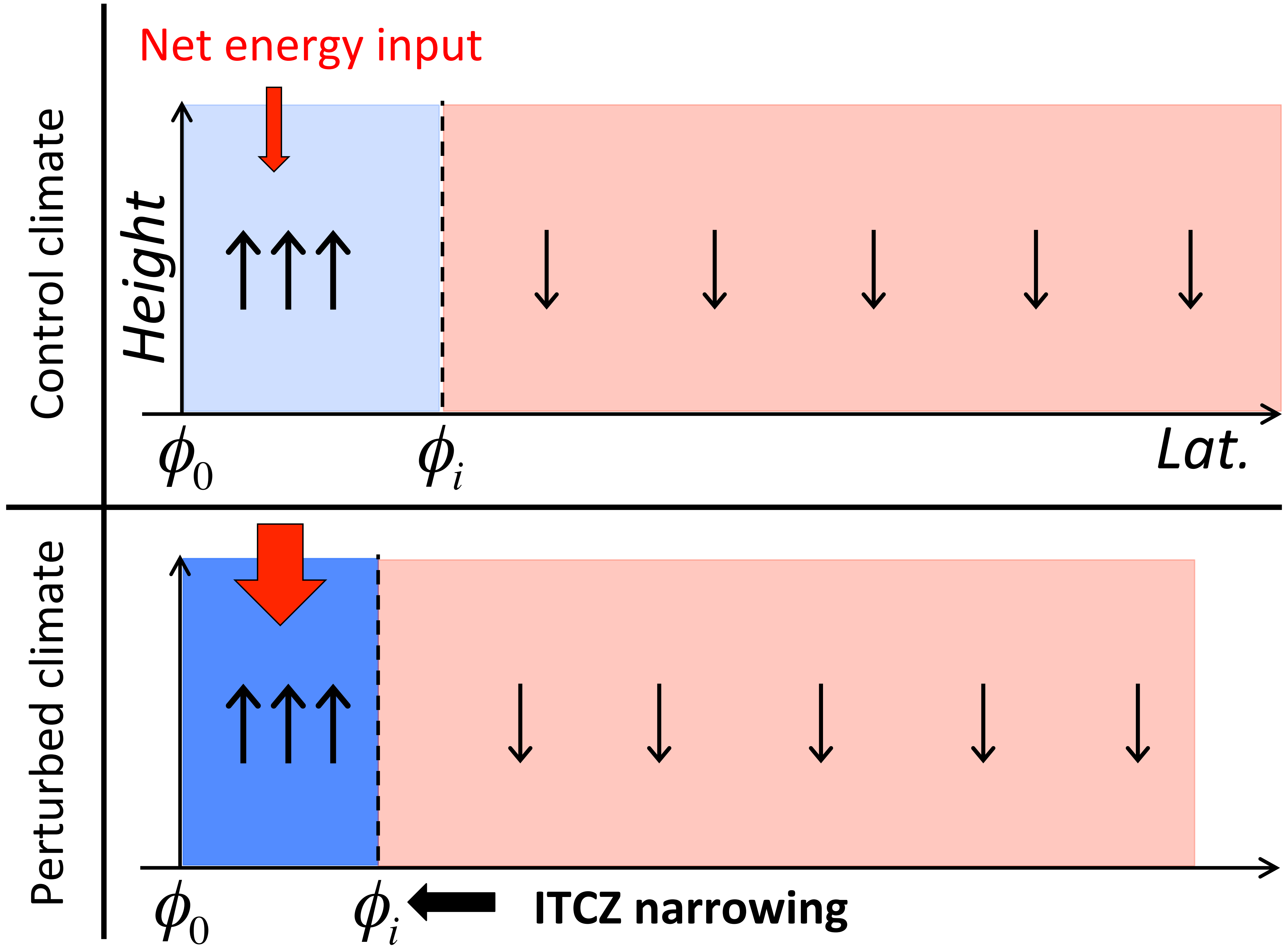
$$|\omega_{\text{itcz}}| \uparrow \quad \Rightarrow \ A_{\text{itcz}} \downarrow$$

(for positive gross moist stability)

Byrne & Schneider, J. Climate (2016)

Energetic perspective on ITCZ width is conceptually useful but diagnostic – useful to consider a complementary dynamical perspective



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Byrne & Schneider, J. Climate (2016)

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Dynamics of ITCZ width: What does simple Ekman balance tell us?

$$f[v] = -(g/\Delta p)\tau_{x,sfc} - \frac{\tan\phi}{a}[uv] + \left[\frac{v}{a}\frac{\partial u}{\partial \phi}\right] + \left[\omega\frac{\partial u}{\partial p}\right]$$

Steady-state zonally-averaged zonal momentum equation (boundary-layer avg):

Byrne & Thomas, JAS (2019)

Dynamics of ITCZ width: What does simple Ekman balance tell us?

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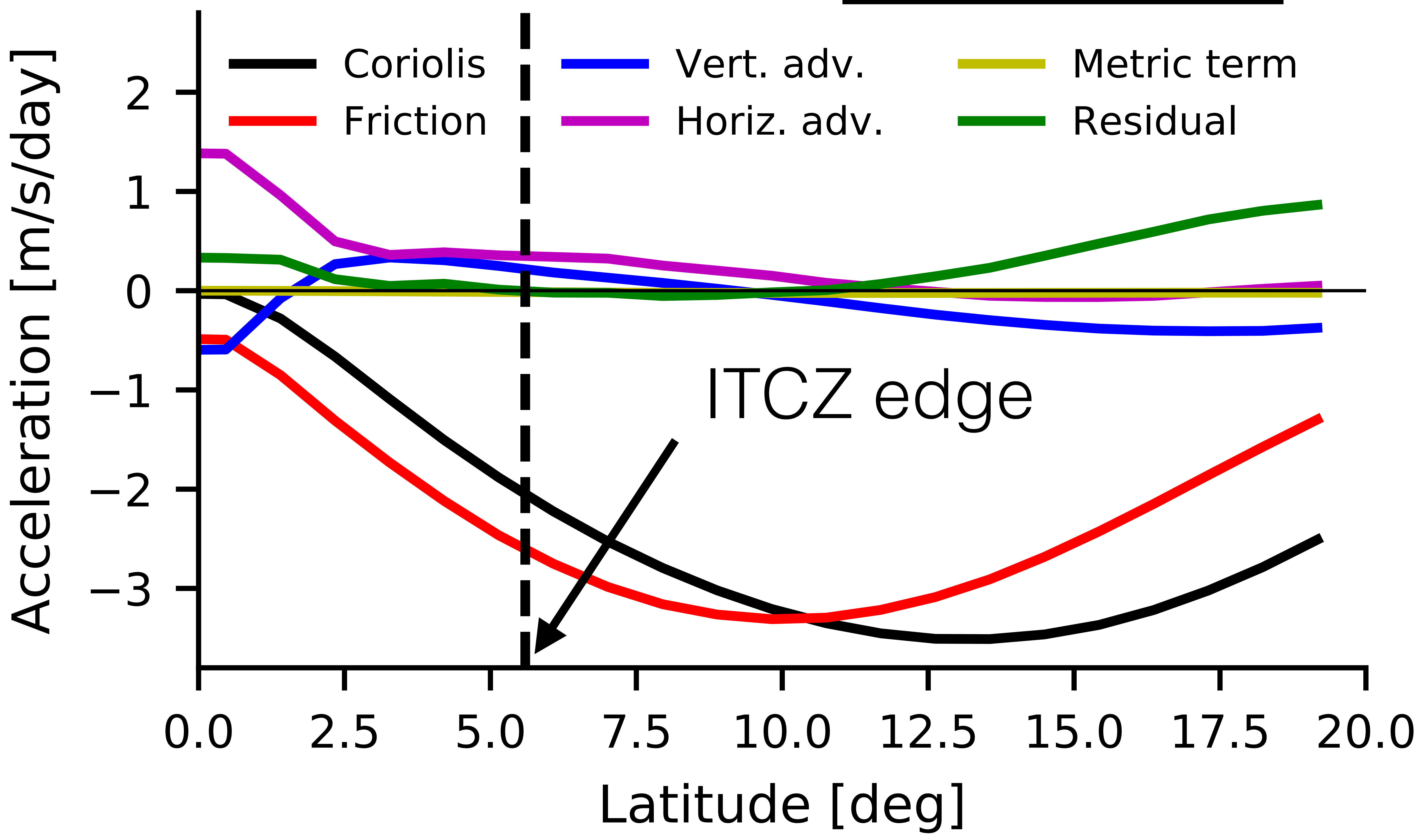
Idealised GCM, control simulation

Steady-state zonally-averaged zonal momentum equation (boundary-layer avg):



Byrne & Thomas, JAS (2019)

Dynamics of ITCZ width: Near the ITCZ edge, boundary layer in ~Ekman balance

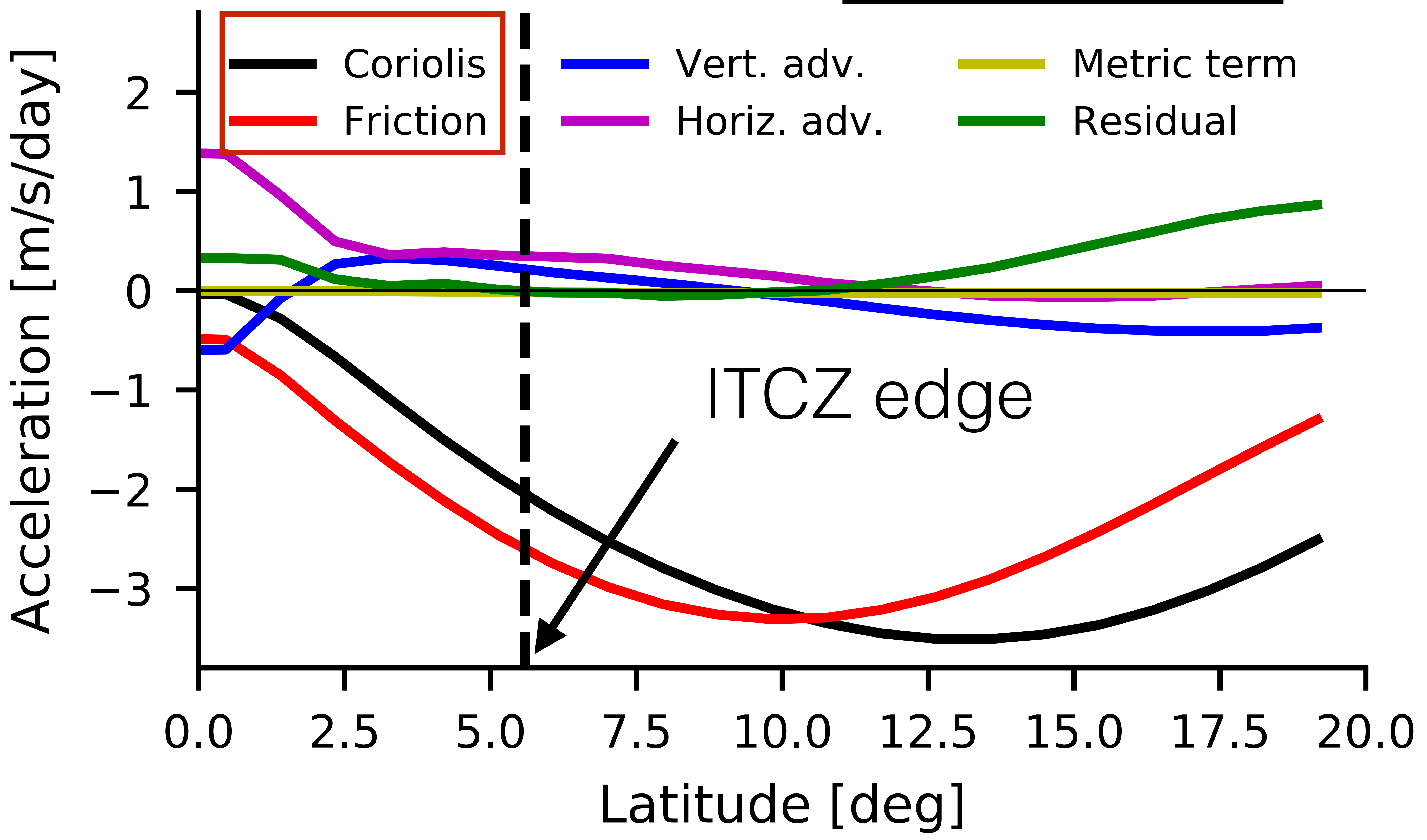
$$\boxed{f[v] = -(g/\Delta p)\tau_{x,sfc}} - \frac{\tan\phi}{a}[uv] + \left[\frac{v}{a}\frac{\partial u}{\partial \phi}\right] + \left[\omega\frac{\partial u}{\partial p}\right]$$

Steady-state zonally-averaged zonal momentum equation (boundary-layer avg):

Approximate Ekman balance near ITCZ —> useful starting point for understanding tropical dynamics *(Lindzen & Nigam 1987; Emanuel 1995; Held 2001; etc)*

Byrne & Thomas, JAS (2019)

Idealised GCM, control simulation



Ekman component of vertical velocity at top of boundary layer

$$\boxed{f[v] = -(g/\Delta p)\tau_{x,sfc}} - \frac{\tan\phi}{a}[uv] + \left[\frac{v}{a}\frac{\partial u}{\partial \phi}\right] + \left[\omega\frac{\partial u}{\partial p}\right]$$

$$\Rightarrow \omega_{\text{ekman}} = -\frac{g}{a}\frac{\partial}{\partial \phi}\left(\frac{\tau_{x,sfc}}{f}\right)$$

= 0 at ITCZ edge by definition (assuming perfect Ekman balance)

assume *ω=0* at surface and that the turbulent stress vanishes at the top of the boundary layer

Byrne & Thomas, JAS (2019)

Simplest estimate of ITCZ edge, ϕ_{ITCZ}: Latitude where surface relative vorticity = 0

$$\boxed{f[v] = -(g/\Delta p)\tau_{x,sfc}} - \frac{\tan\phi}{a}[uv] + \left[\frac{v}{a}\frac{\partial u}{\partial \phi}\right] + \left[\omega\frac{\partial u}{\partial p}\right]$$

$$\Rightarrow \omega_{\mathrm{ekman}} = -\frac{g}{a}\frac{\partial}{\partial \phi}\left(\frac{\tau_{x,sfc}}{f}\right)$$

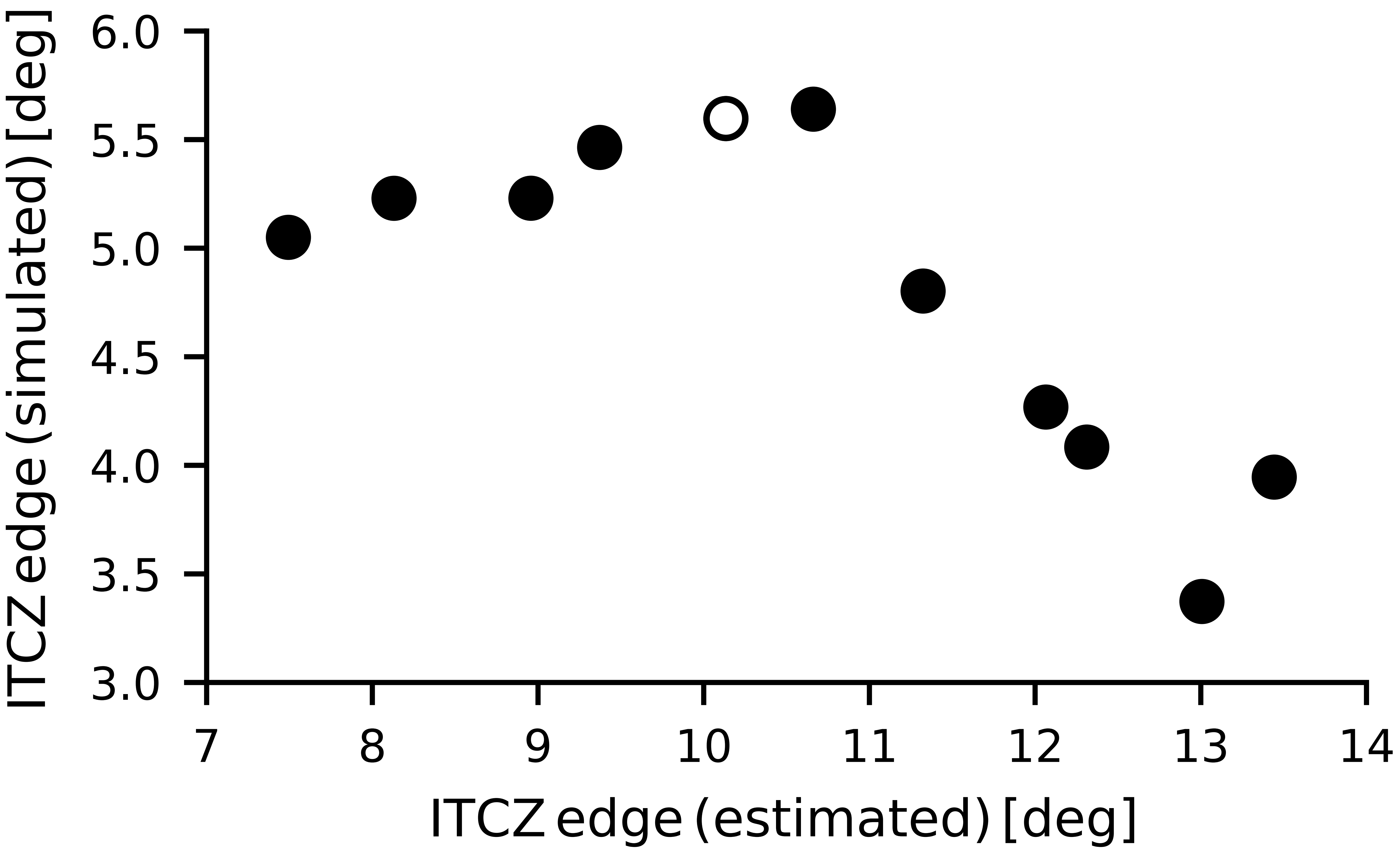
= 0 at ITCZ edge by definition (assuming perfect Ekman balance)

$$\Rightarrow \phi_{\mathrm{ITCZ}} \text{ where } \frac{\partial \tau_{x,sfc}}{\partial \phi} \sim \boxed{\frac{\partial u_{sfc}}{\partial \phi} = 0}$$

Simplest estimate of ITCZ edge: Latitude where surface relative vorticity = 0. Ignores convergence driven by *d(1/f)/d*ϕ term… Does it work?

Byrne & Thomas, JAS (2019)

Simplest Ekman estimate of ITCZ edge… Too simple!



(same idealised GCM simulations as before in which LW optical depth is varied)

Byrne & Thomas, JAS (2019)

Modified Ekman scaling for ITCZ edge taking into account strong gradient in *1/f*

$$\omega_{\text{ekman}} = -\frac{g}{a}\frac{\partial}{\partial\phi}\left(\frac{\tau_{x,sfc}}{f}\right)$$

$$\Rightarrow 0 = -\frac{g}{fa}\frac{\partial\tau_{x,sfc}}{\partial\phi} - \frac{g}{a}\tau_{x,sfc}\frac{\partial}{\partial\phi}\left(\frac{1}{f}\right) \text{ at ITCZ edge}$$

Byrne & Thomas, JAS (2019)

Modified Ekman scaling for ITCZ edge taking into account strong gradient in *1/f*

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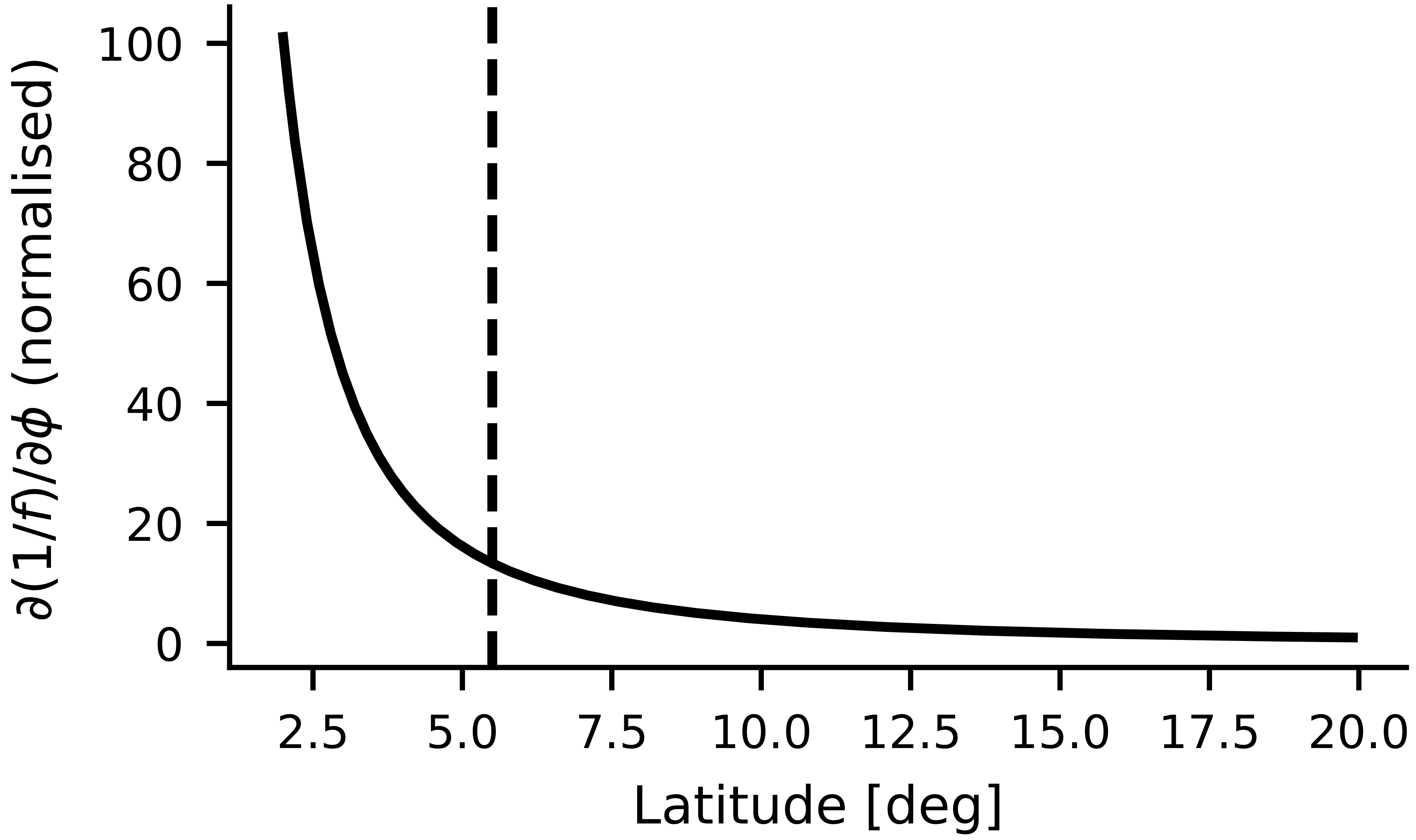

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Use this scaling and a toy model to develop physical intuition for how ITCZ width responds to wind-stress perturbations

Making small-angle approximation: $f = 2\Omega \sin\phi \approx 2\Omega\phi$

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Byrne & Thomas, JAS (2019)

Physical insights into ITCZ width from Ekman balance: toy model

Setup of toy model:

- Assume a tropical boundary layer in Ekman balance
- Prescribe a zonal wind stress and balanced meridional flow
- Perturb wind stress in simple ways to investigate effects on ITCZ width

$$\tau_{\mathrm{ref}}(\phi) = v_{max} \times (f\Delta p/g)\sin 9\phi$$

$$v_{\mathrm{ref}}(\phi) = v_{max}\sin 9\phi$$

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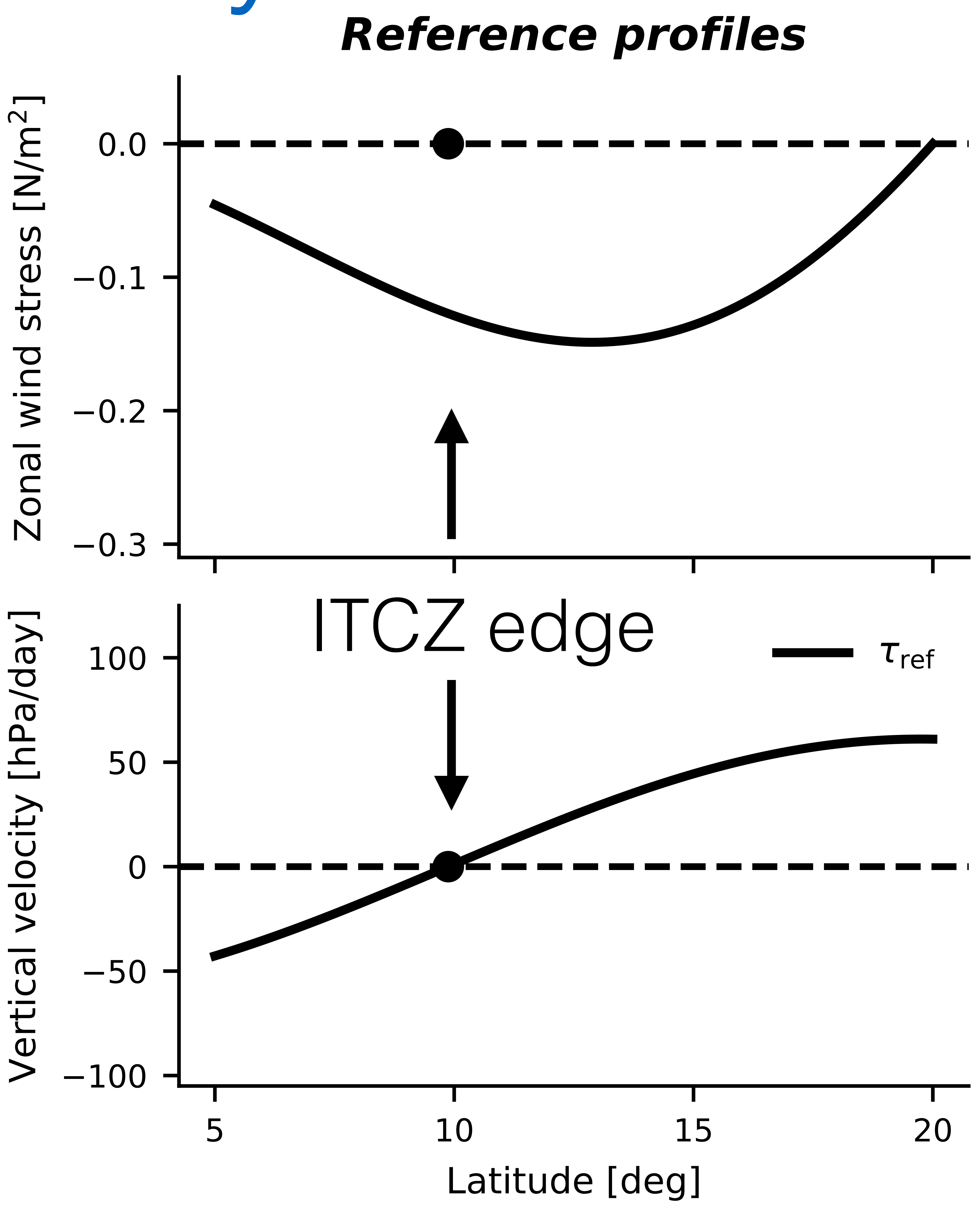

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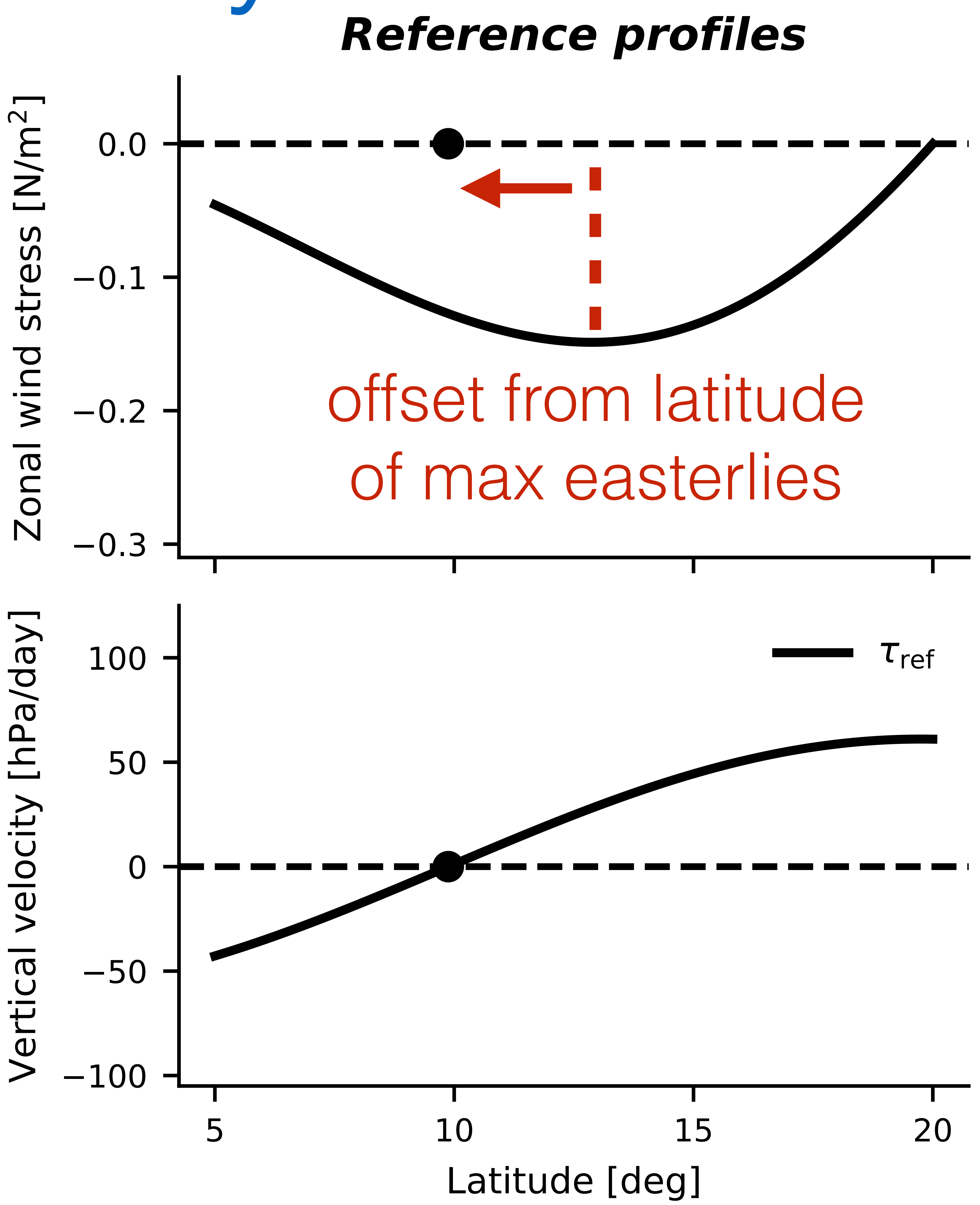

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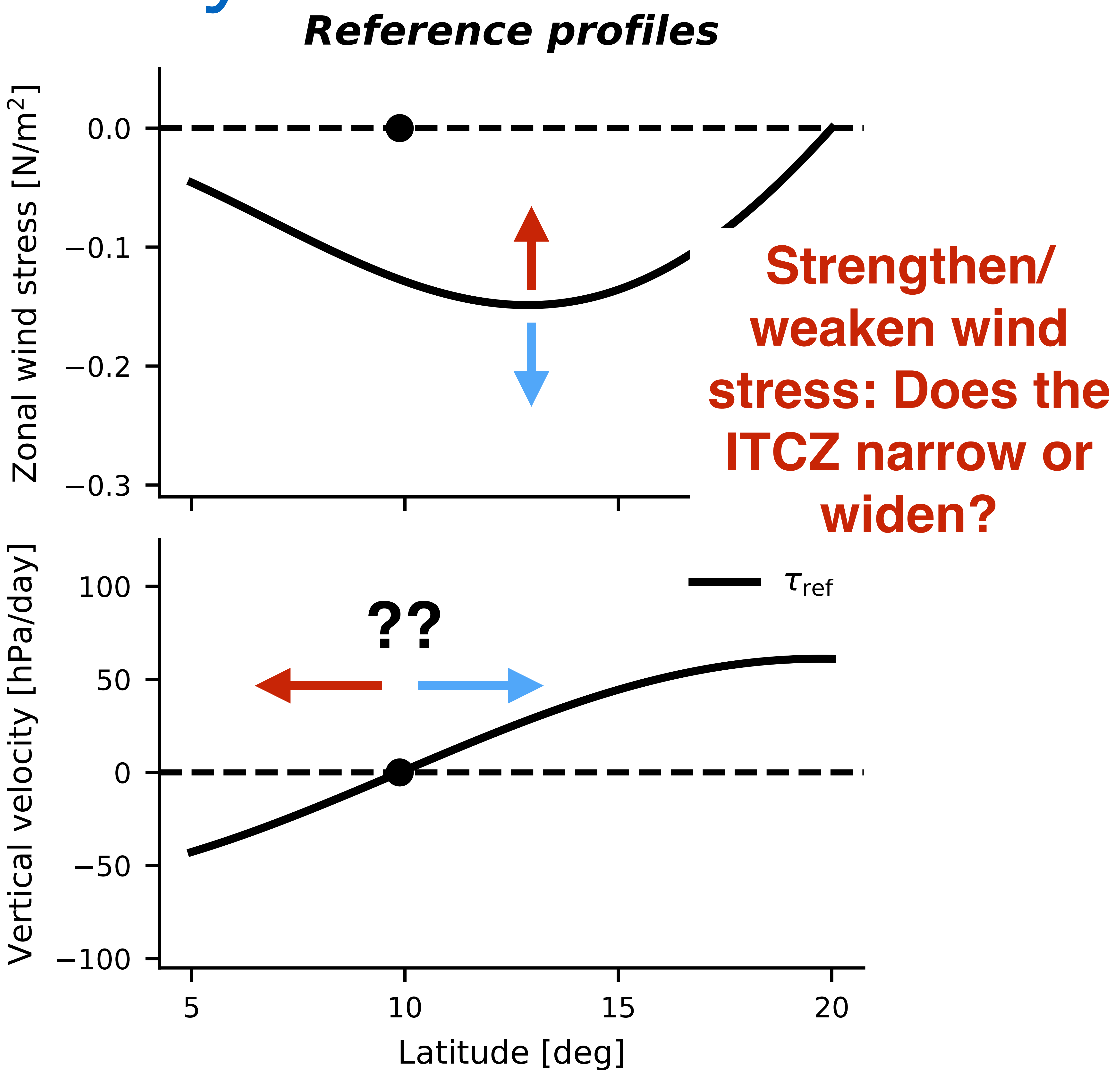
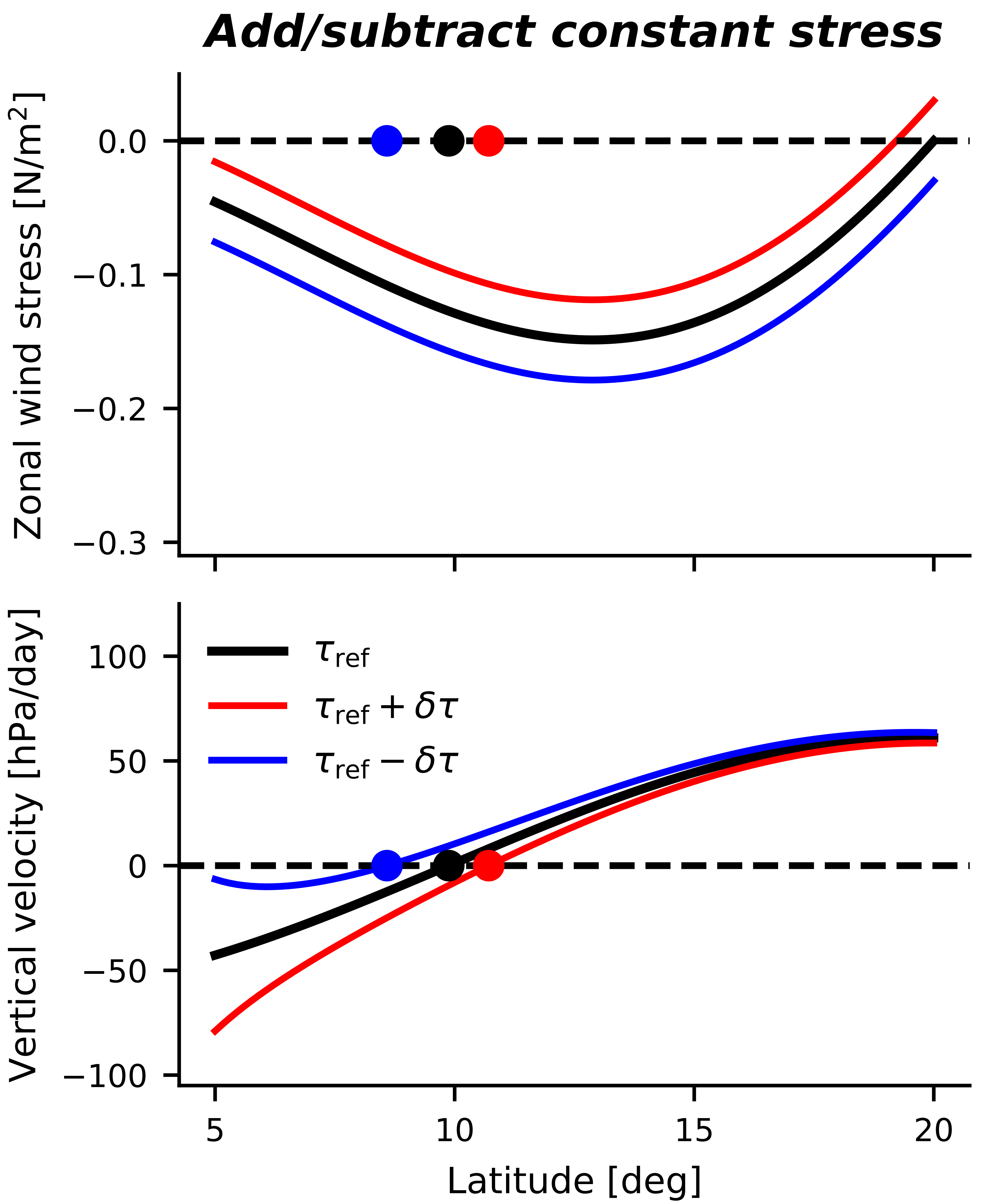


Adding a constant westerly wind perturbation widens the ITCZ; easterly perturbation narrows the ITCZ



Byrne & Thomas, JAS (2019)

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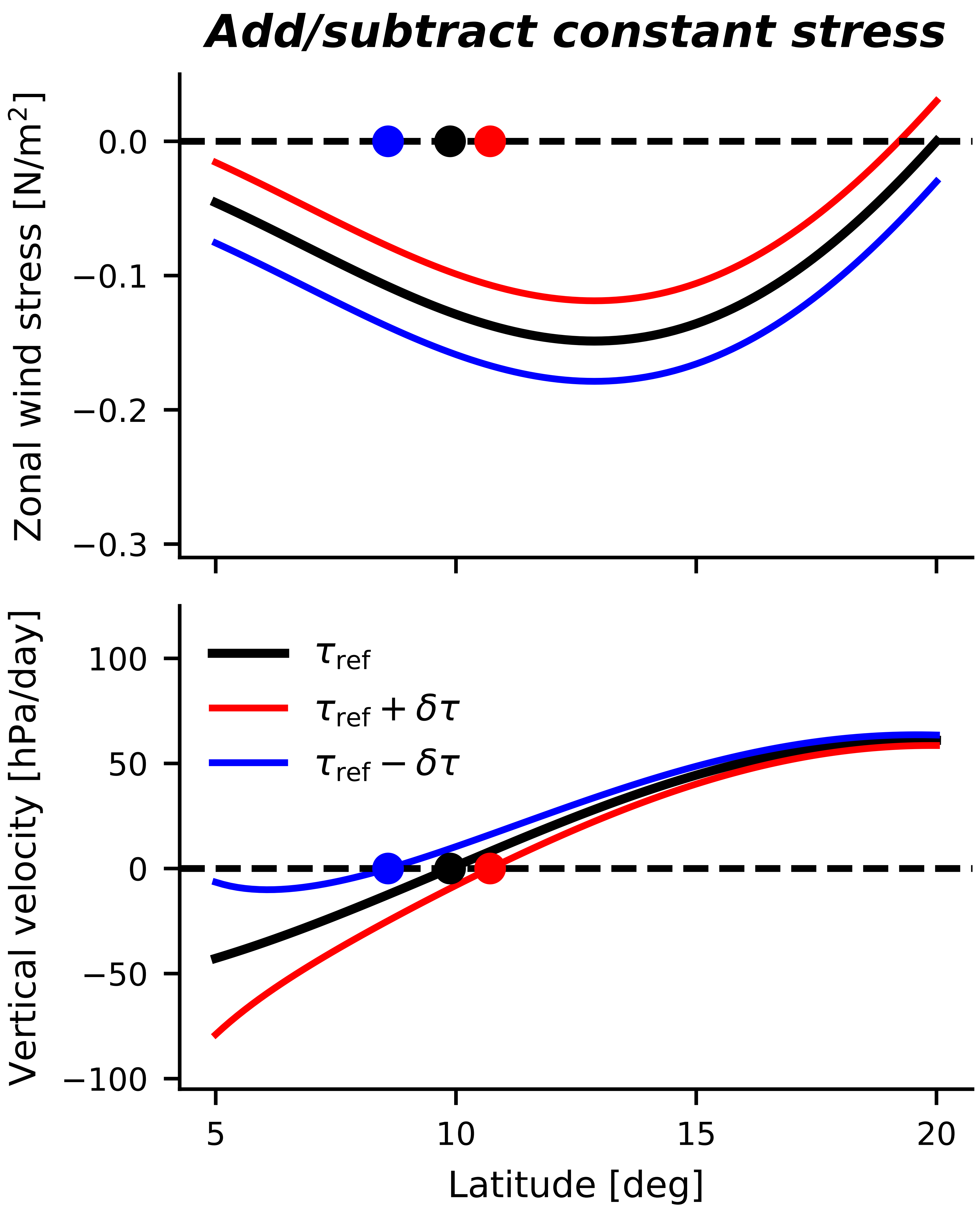
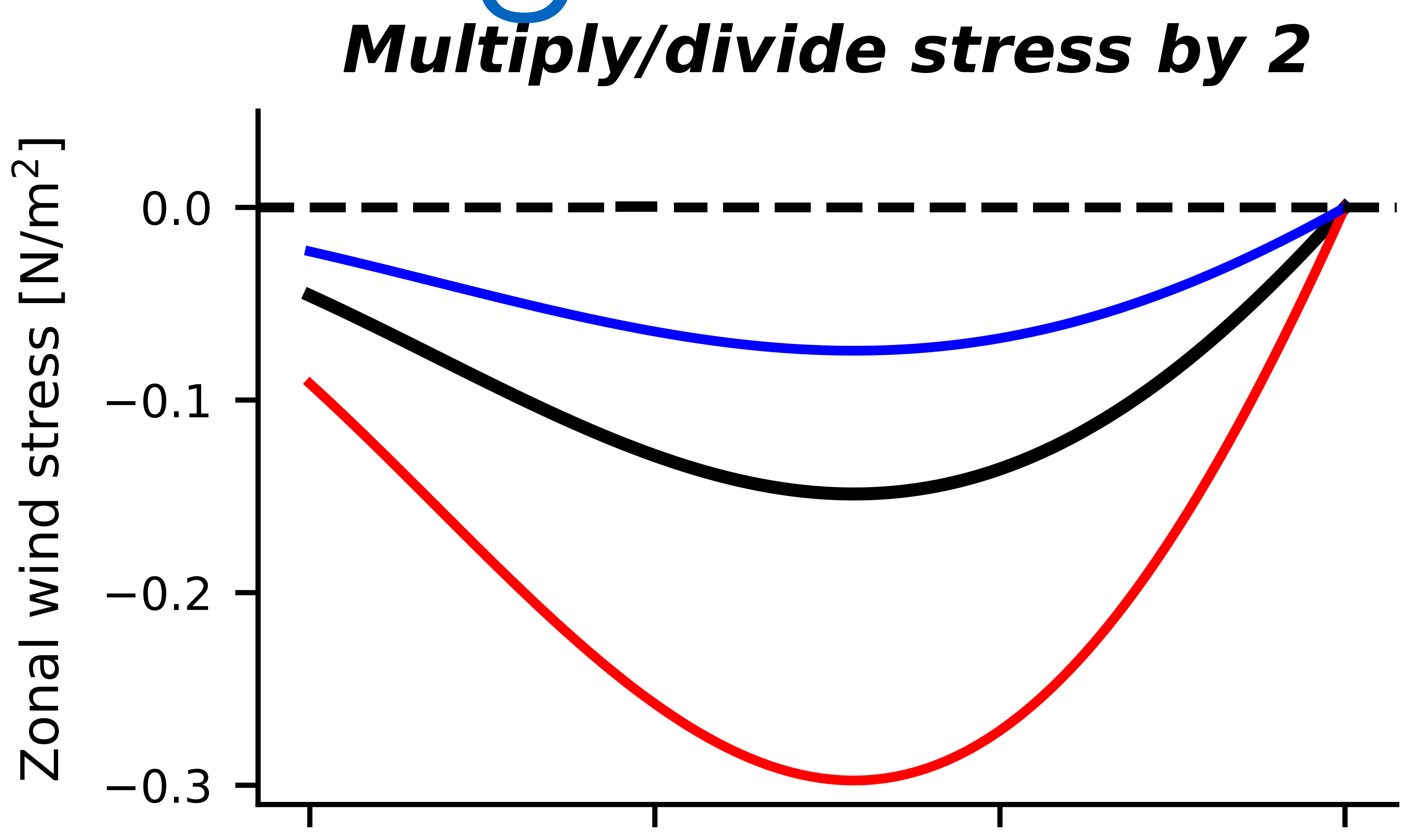
Perturbation analysis of Ekman scaling gives prediction of shift in ITCZ edge due to constant change in wind stress, $\delta\tau$:

$$\delta\phi_{\mathrm{ITCZ}} \approx \frac{1}{\phi_{\mathrm{ITCZ}}} \left. \frac{\delta\tau}{\partial^2\tau_{x,sfc}/\partial\phi^2} \right|_{\phi_{\mathrm{ITCZ}}}$$

Byrne & Thomas, JAS (2019)



Multiply wind stress by constant factor: How does the ITCZ edge shift?



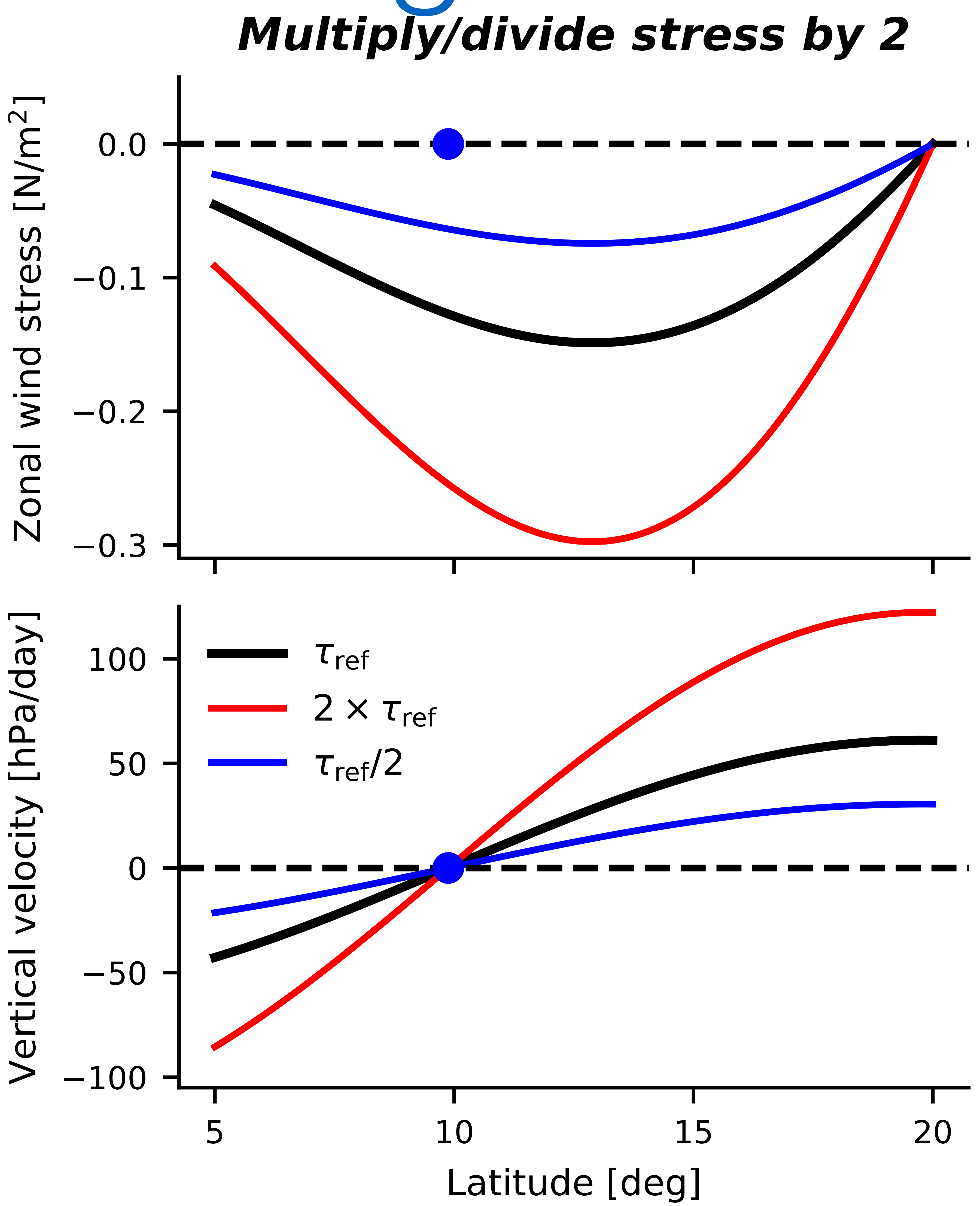
Byrne & Thomas, JAS (2019)

Multiply wind stress by constant factor: No shift in ITCZ edge

Scaling wind stress by a constant factor does not shift ITCZ edge —> competing effects of changes in magnitude and gradient of wind stress cancel out

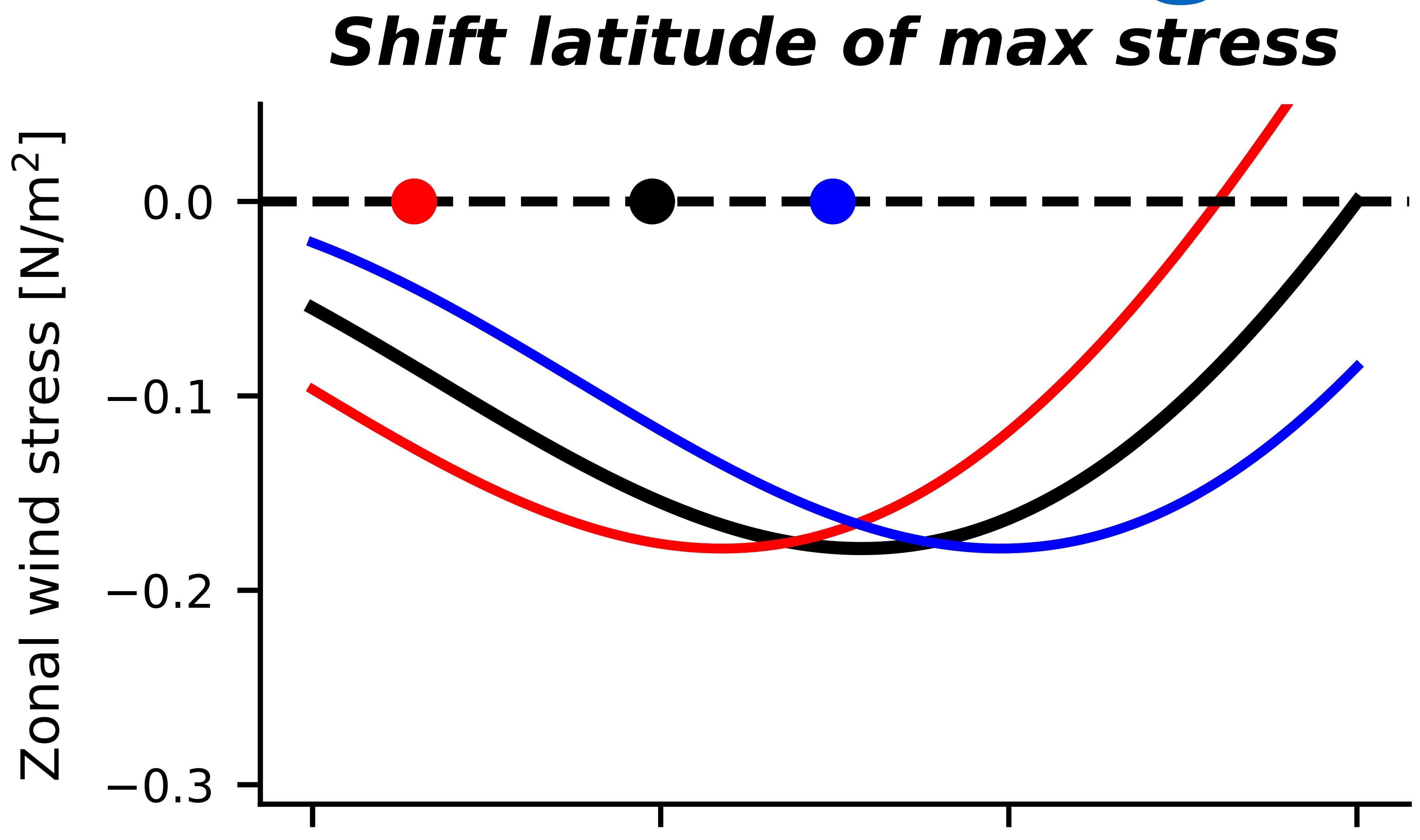
$$\Rightarrow \phi_{\mathrm{ITCZ}}^{\mathrm{ekman}} = \tau_{x,sfc}(\phi_{\mathrm{ITCZ}}) / \left. \frac{\partial \tau_{x,sfc}}{\partial \phi} \right|_{\phi=\phi_{\mathrm{ITCZ}}}$$

Byrne & Thomas, JAS (2019)



Small shifts in latitude of max wind stress cause amplified shifts in ITCZ edge

Perhaps intuitively, shifting latitude of max wind stress equatorward narrows the ITCZ



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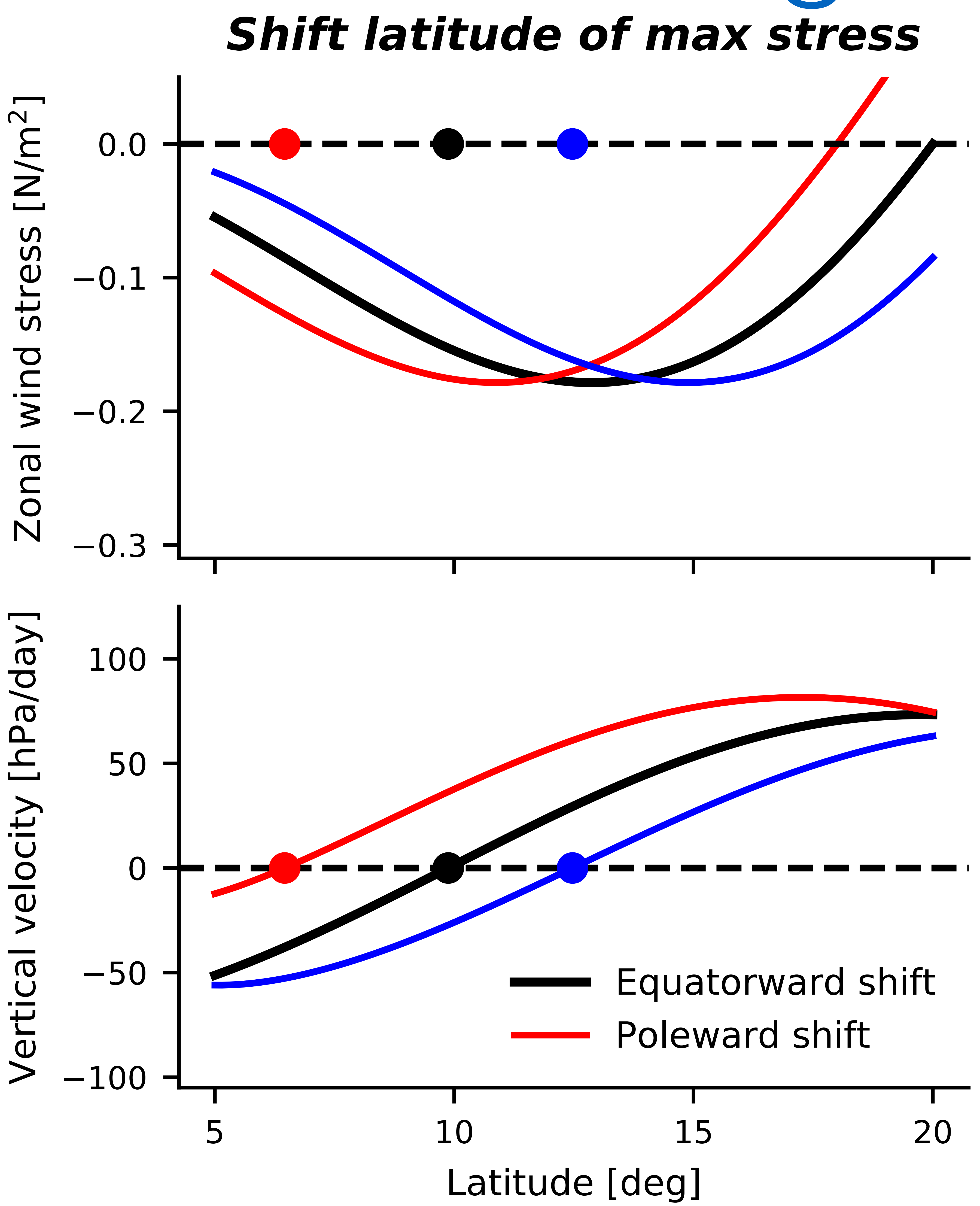
How does the Ekman scaling perform when applied to the idealized GCM?

Byrne & Thomas, JAS (2019)



Returning to the GCM: Ekman scaling has some skill capturing variations across simulations, but systematically overestimates ITCZ width

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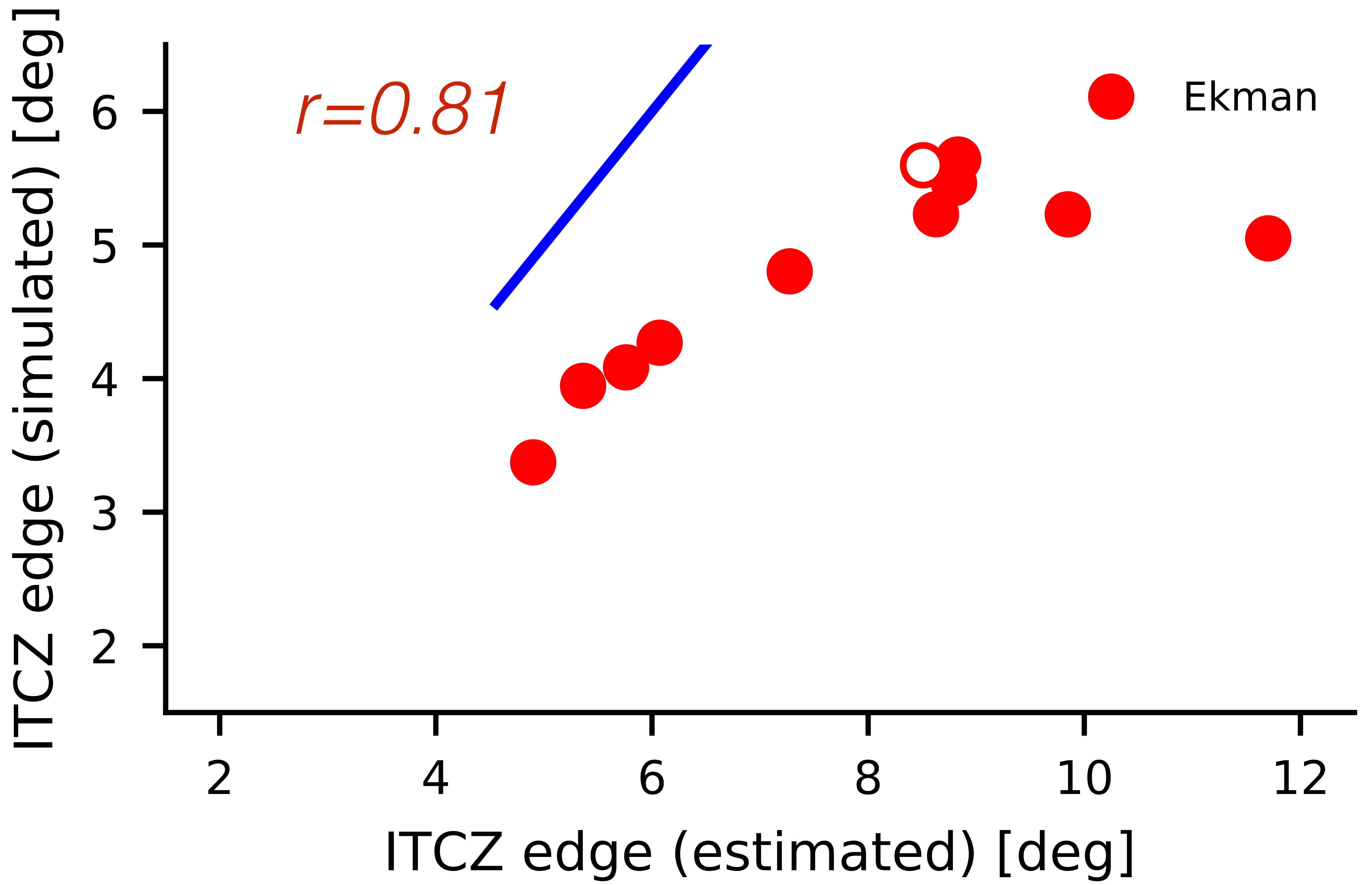
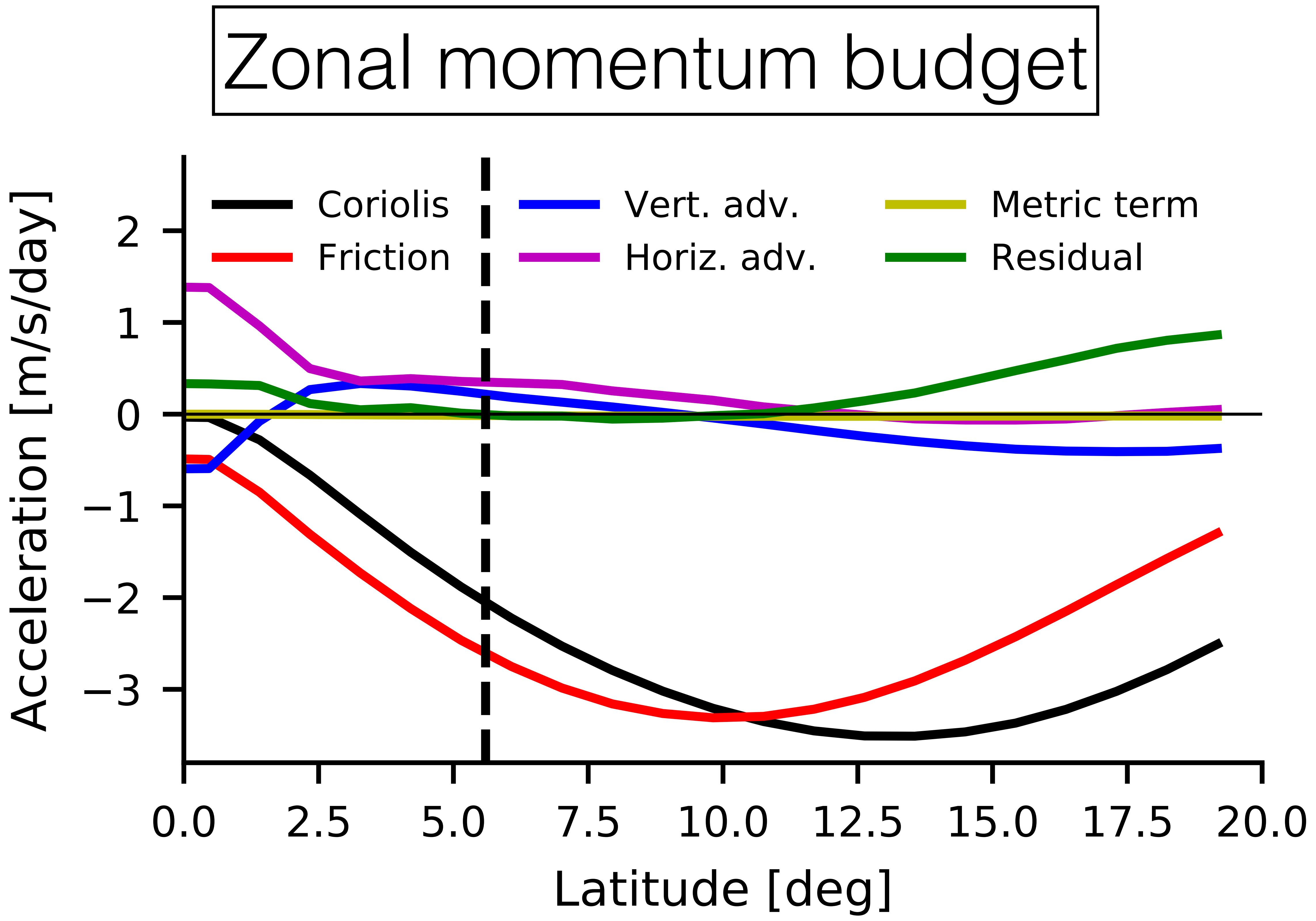


Byrne & Thomas, JAS (2019)

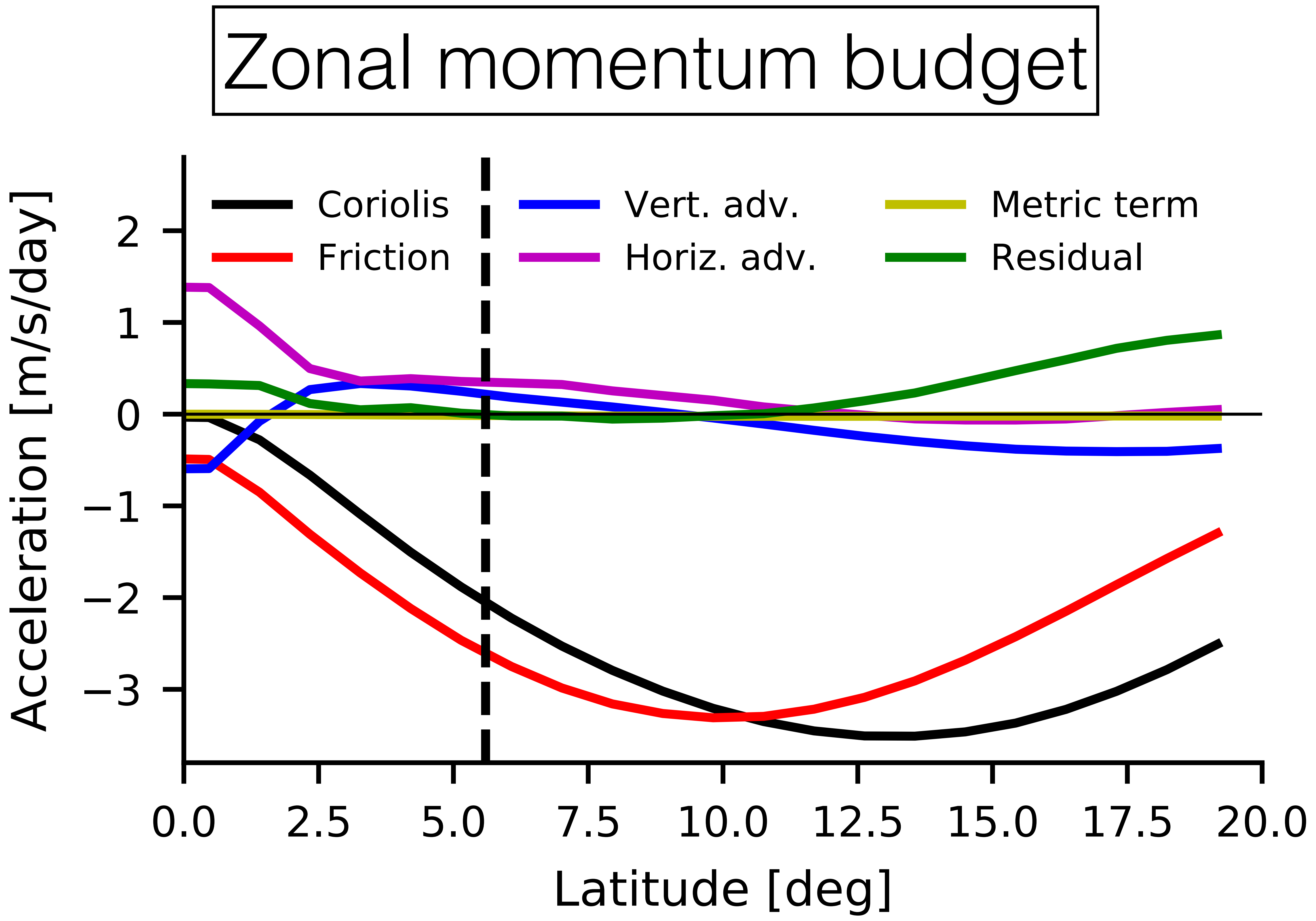
Beyond Ekman dynamics: Although momentum advection is relatively small in boundary layer…



$$f[v] = -(g/\Delta p)\tau_{x,sfc} - \frac{\tan\phi}{a}[uv] + \left[\frac{v}{a}\frac{\partial u}{\partial \phi}\right] + \left[\omega\frac{\partial u}{\partial p}\right]$$

Byrne & Thomas, JAS (2019)

Beyond Ekman dynamics: Although momentum advection is relatively small in boundary layer, it has a large influence on vertical velocity at ITCZ edge



$$\omega_{\text{total}} = \underbrace{-\frac{g}{a\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\tau_{x,\text{sfc}}}{f}\cos\phi\right)}_{\omega_{\text{ekman}}} \underbrace{+\frac{\Delta p}{a\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\cos\phi}{f}\left[\omega\frac{\partial u}{\partial p}\right]\right)}_{\omega_{\text{vert}}} \underbrace{+\frac{\Delta p}{a\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\cos\phi}{f}\left[\frac{v}{a}\frac{\partial u}{\partial\phi}\right]\right)}_{\omega_{\text{horiz}}}$$

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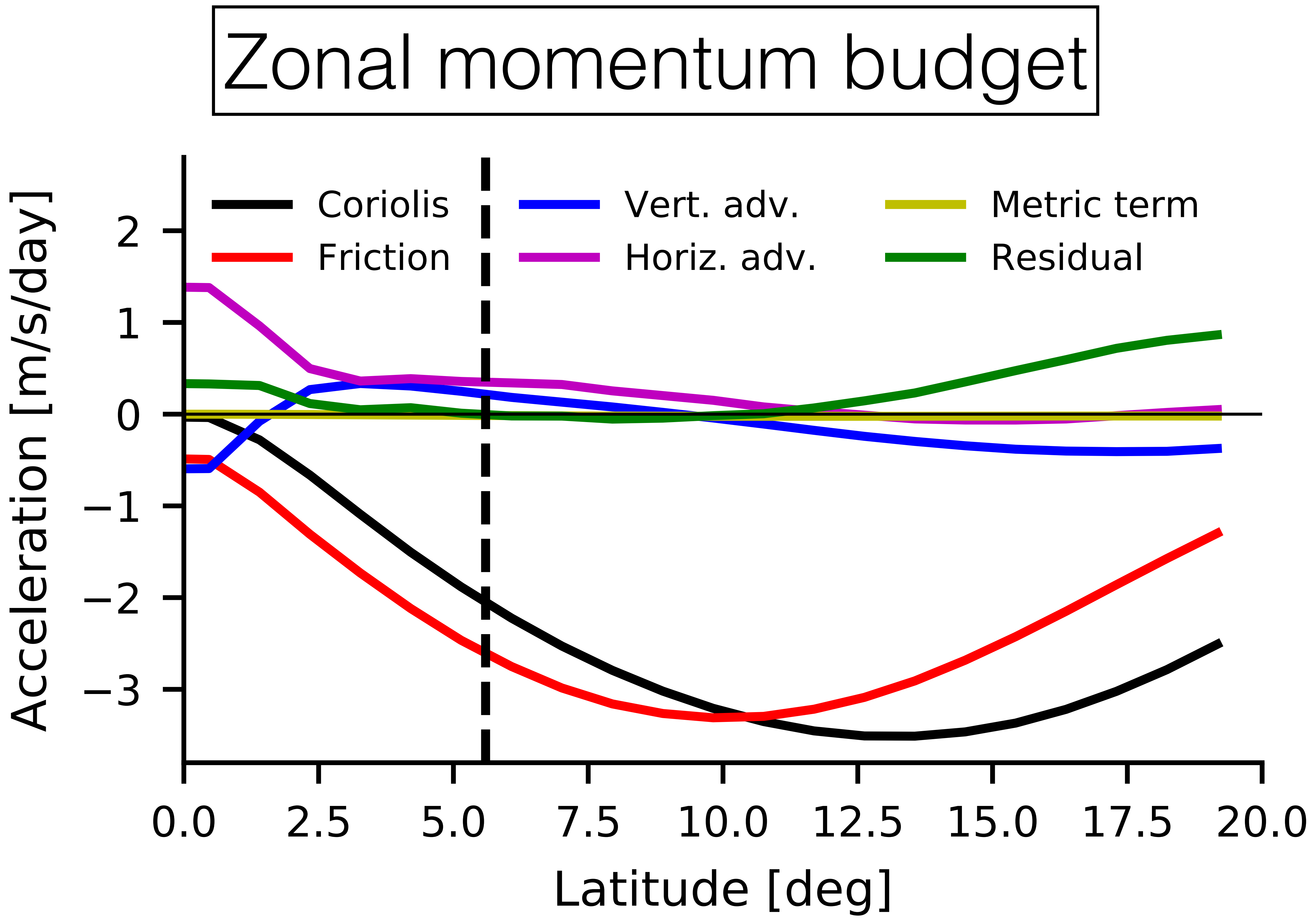

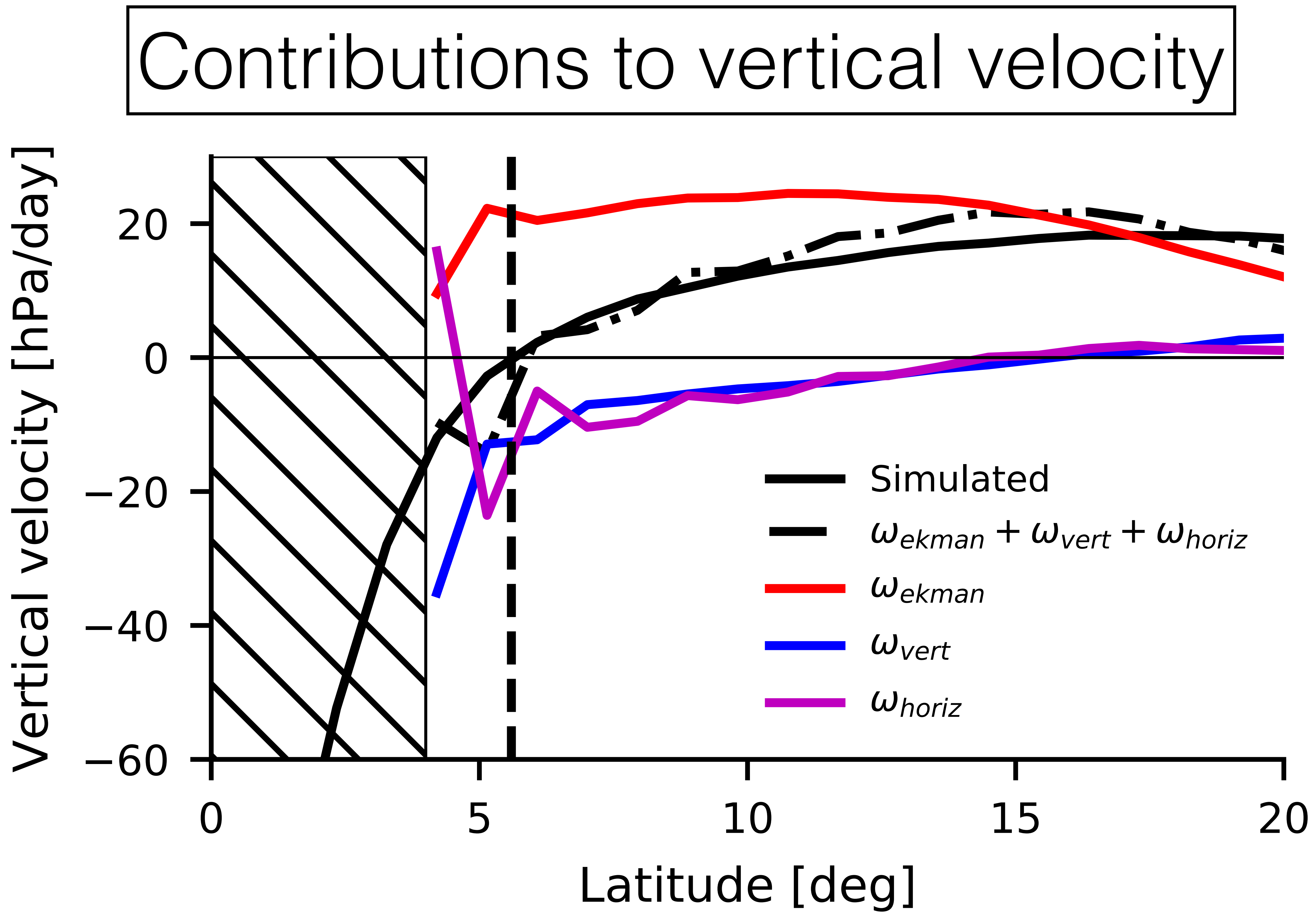

Byrne & Thomas, JAS (2019)

Full scaling for ITCZ width: Quantitative theory needs to include horizontal and vertical momentum advection

$$\phi_{\mathrm{ITCZ}}^{\mathrm{full}} = \left. \frac{-(g/\Delta p)\tau_{x,\mathrm{sfc}} + \left[\omega \frac{\partial u}{\partial p}\right] + \left[\frac{v}{a}\frac{\partial u}{\partial \phi}\right]}{-(g/\Delta p)\frac{\partial \tau_{x,\mathrm{sfc}}}{\partial \phi} + \frac{\partial}{\partial \phi}\left[\omega \frac{\partial u}{\partial p}\right] + \frac{\partial}{\partial \phi}\left[\frac{v}{a}\frac{\partial u}{\partial \phi}\right]} \right|_{\phi=\phi_{\mathrm{ITCZ}}}$$

Importance of momentum advection for tropical winds noted previously *(Holton 1975; Stevens et al 2002; Back & Bretherton 2009; Gonzalez et al 2016)*

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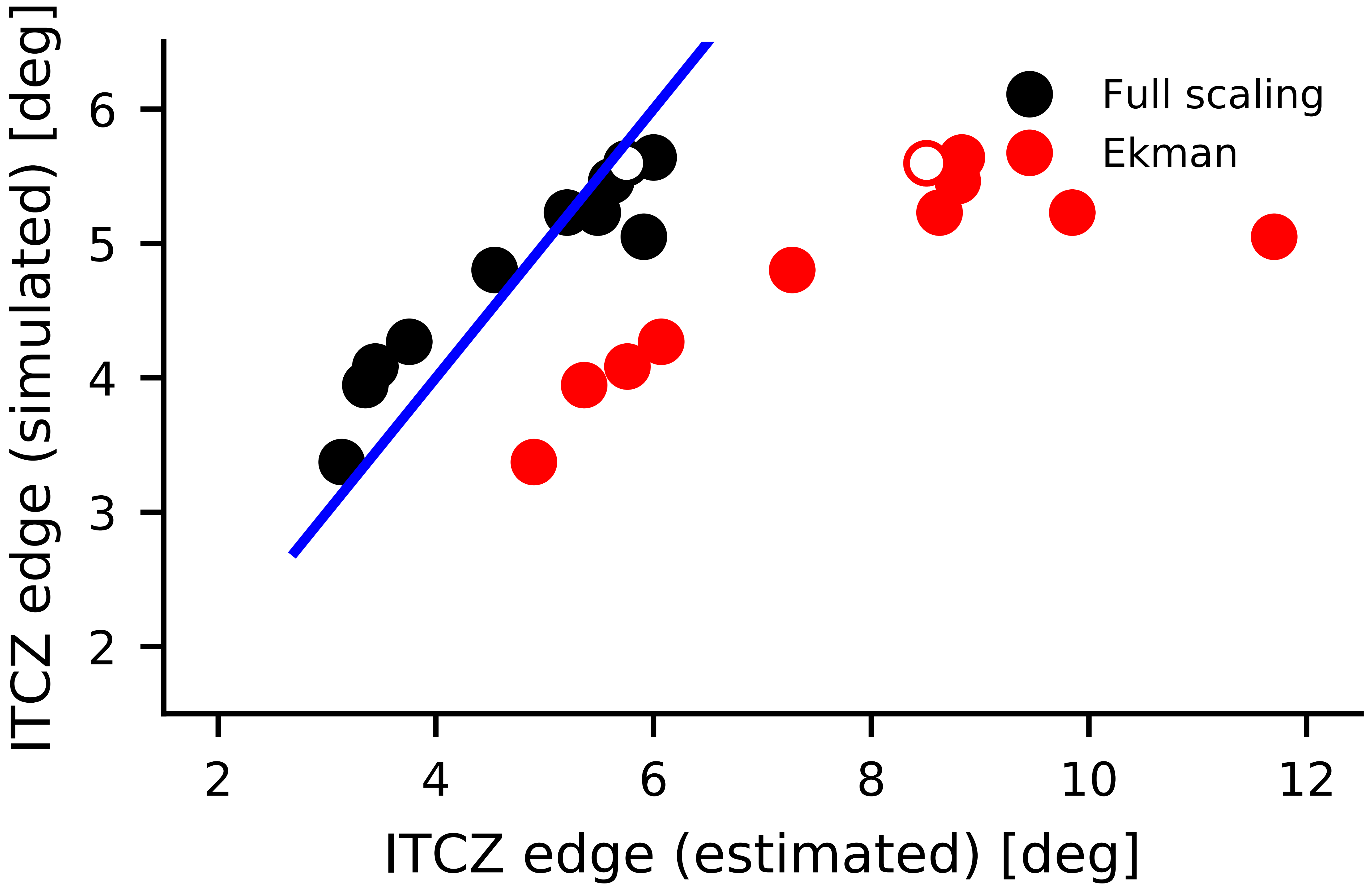

Byrne & Thomas, JAS (2019)

Linking ITCZ width to sea-surface temperature

- Traditional in atmospheric dynamics to construct theories connecting tropical circulation to SST *(e.g. Lindzen & Nigam 1987; Sobel 2007)*
- Following *L&N*, we assume Ekman balance and combine the zonal and meridional momentum equations to obtain:

$$[v] = -\frac{C}{f^2 + C^2}\left[\frac{1}{\rho a}\frac{\partial p}{\partial \phi}\right]$$

Byrne & Thomas, JAS (2019)

Linking ITCZ width to sea-surface temperature

$$[v] = -\frac{C}{f^2 + C^2}\left[\frac{1}{\rho a}\frac{\partial p}{\partial \phi}\right]$$

- Assuming zero pressure gradients above the boundary layer, use ideal gas law to link boundary-layer pressure gradient to SST gradient:

$$[v] \propto -\frac{\partial p}{\partial \phi} \propto \frac{\partial SST}{\partial \phi}$$

Byrne & Thomas, JAS (2019)

Linking ITCZ width to sea-surface temperature: ITCZ edge scales with latitude where Laplacian of SST = 0??

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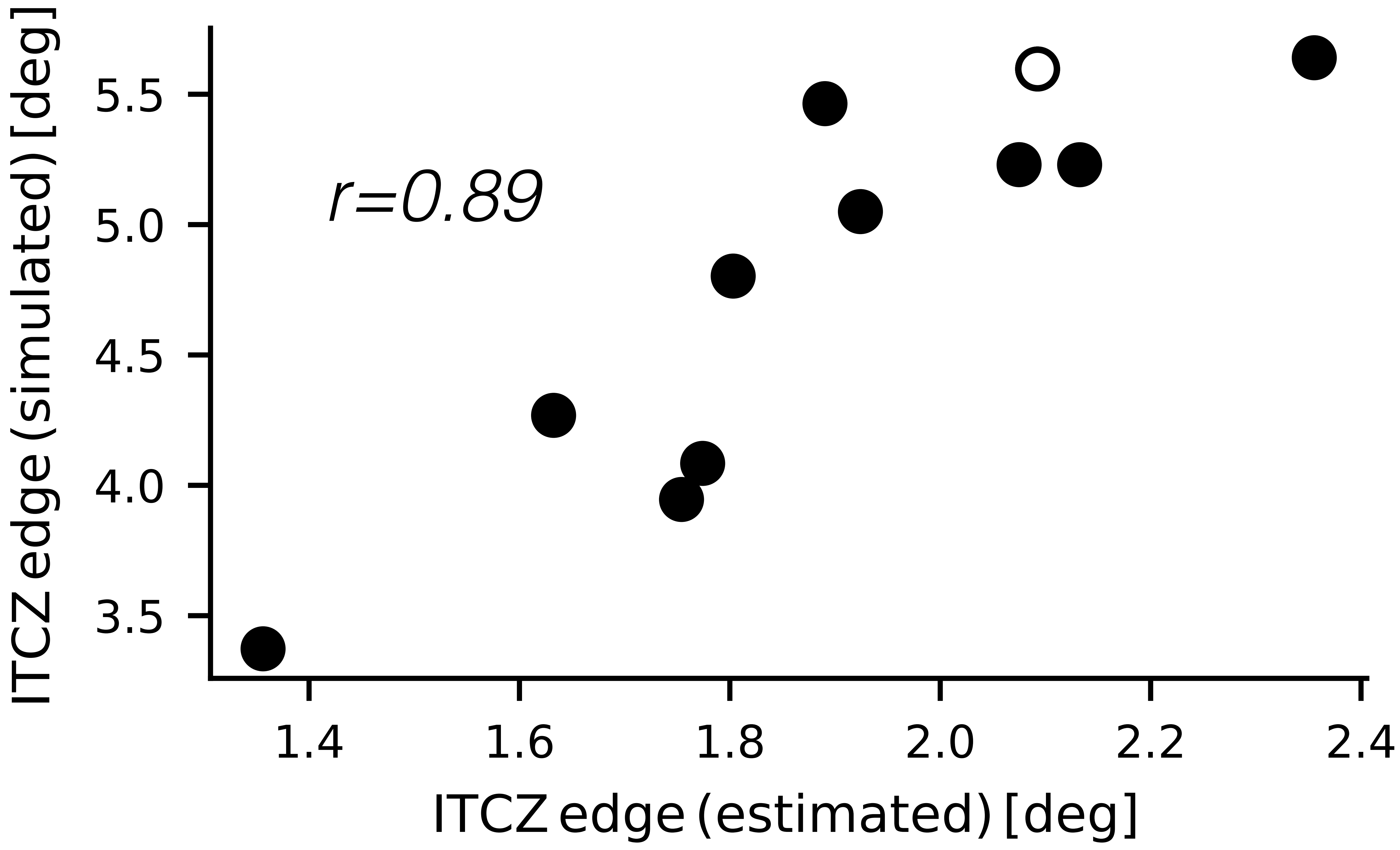
Byrne & Thomas, JAS (2019)

Linking ITCZ width to sea-surface temperature: Strong relationship between ITCZ width and curvature of SST



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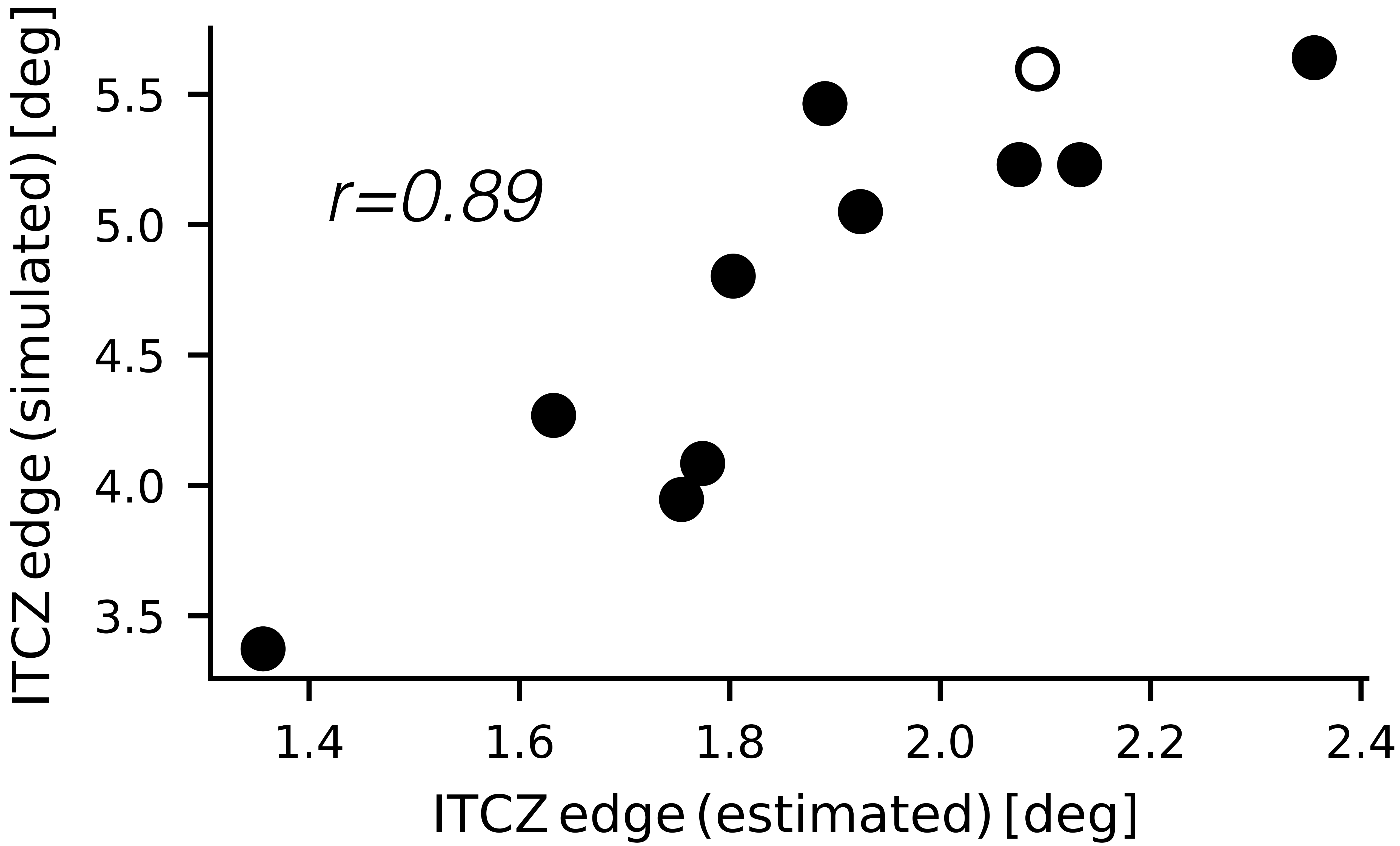

$$\omega \propto \frac{\partial^2 SST}{\partial \phi^2}$$

- Strong correlation between ITCZ edge and latitude where Laplacian/curvature of SST = 0
- Offset due to neglecting momentum advection, “back pressure” term and *1/f*² gradient

Byrne & Thomas, JAS (2019)

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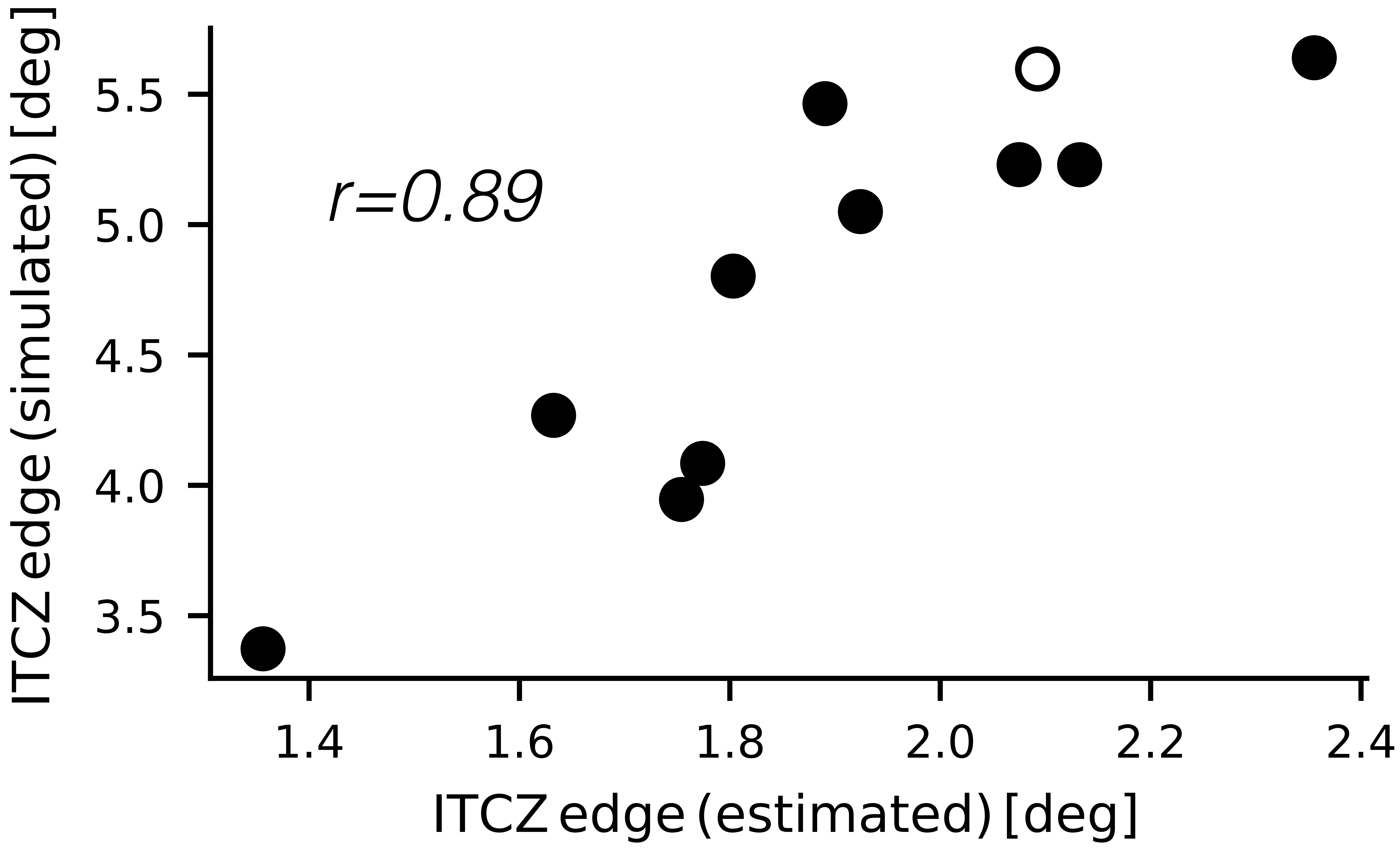

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- Strong correlation between ITCZ edge and latitude where Laplacian/curvature of SST = 0
- Offset due to neglecting momentum advection, "back pressure" term and *1/f²* gradient
- **Potential to be predictive, given a change in SST**
- **Useful for explaining narrowing of the ITCZ under global warming?**

Byrne & Thomas, JAS (2019)

Summary

- **ITCZ expected to narrow and weaken with global warming**
- **Strong relationship between changes in ITCZ width and strength**, ideas emerging to understand this (*e.g. Su et al 2019*)

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- **Ongoing work on links between ITCZ width and global climate:** Why do warmer simulations have wider ITCZs? A causal relationship? What are the dynamical mechanisms linking ITCZ width to Hadley Cell edge and poleward expansion?

For further information…

1. Byrne & Thomas (2019): **"Dynamics of ITCZ width: Ekman processes, non-Ekman processes and links to SST"**, *Journal of the Atmospheric Sciences*

2. Byrne, Pendergrass, Rapp & Wodzicki (2018): **"Response of the ITCZ to climate change: location, width and strength"**, *Current Climate Change Reports*

3. Byrne & Schneider (2016): **"Narrowing of the ITCZ in a warming climate: physical mechanisms"**, *Geophysical Research Letters*

4. Byrne & Schneider (2016): **"Energetic constraints on the width of the ITCZ"**, *Journal of Climate*

Thanks!

Why is there a strong anti-correlation between changes in ITCZ width and strength?

Fractional changes in total mass transport by ITCZ:

$$\frac{\delta\Psi_{\mathrm{ITCZ}}}{\Psi_{\mathrm{ITCZ}}} = \frac{\delta\omega_{\mathrm{ITCZ}}}{\omega_{\mathrm{ITCZ}}} + \frac{\delta W_{\mathrm{ITCZ}}}{W_{\mathrm{ITCZ}}}$$

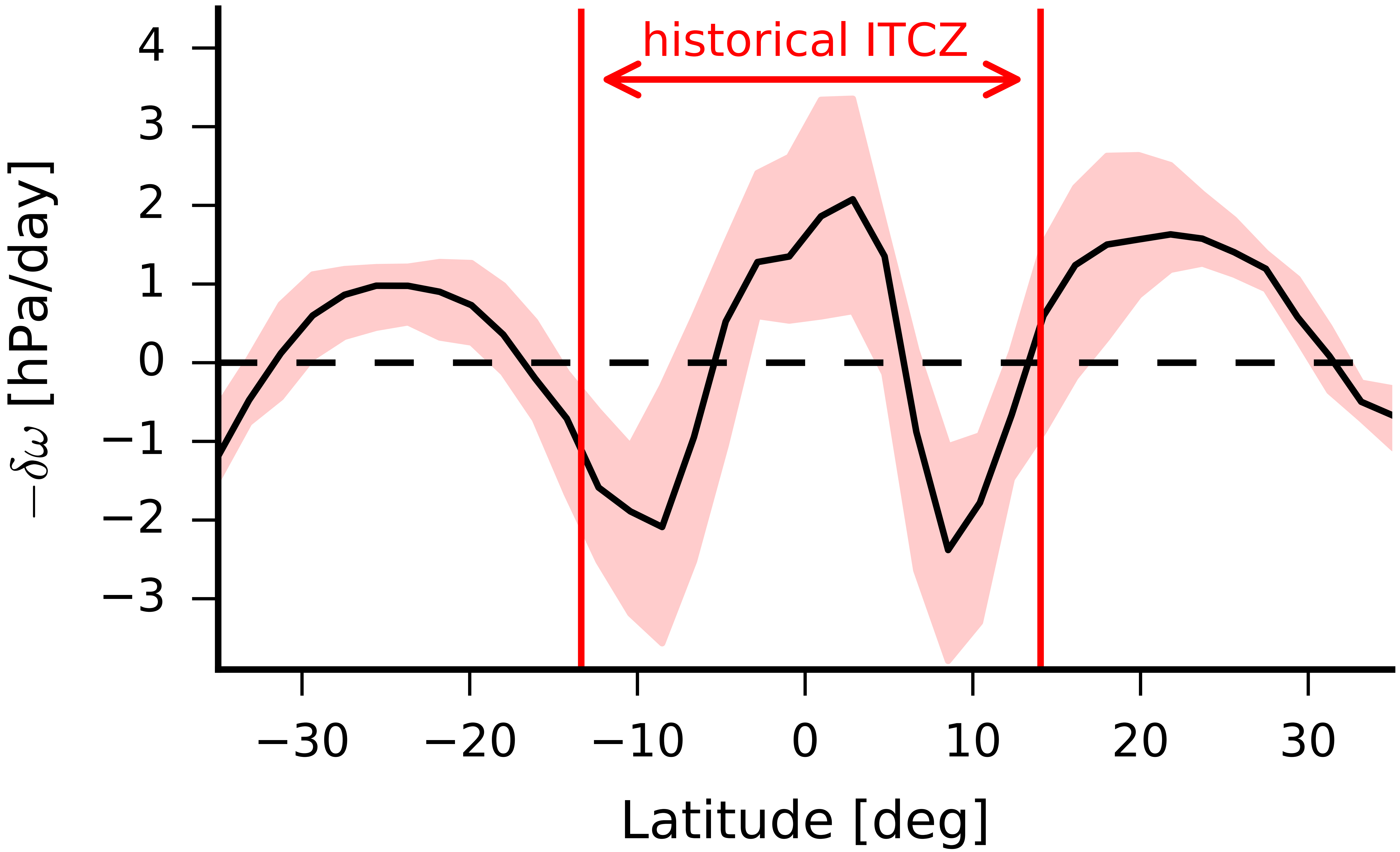
Changes in global mass circulation constrained by fractional changes in *P* and *q (Held & Soden 2006)*:

$$\frac{\delta\Psi_{\mathrm{global}}}{\Psi_{\mathrm{global}}} = \frac{\delta P_{\mathrm{global}}}{P_{\mathrm{global}}} - \frac{\delta q_{\mathrm{global}}}{q_{\mathrm{global}}} \approx -5\%/\mathrm{K}$$

Assuming the changes in ITCZ mass flux follow the global constraint (not unreasonable considering the majority of Earth's rainfall falls in ITCZ) then sum of fractional changes in width and strength is constrained – anti-correlated

Byrne et al, CCCR, submitted

Structure of ITCZ circulation changes



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