# ITCZ width and its sensitivity to changes in climate

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Model Hierarchies Workshop
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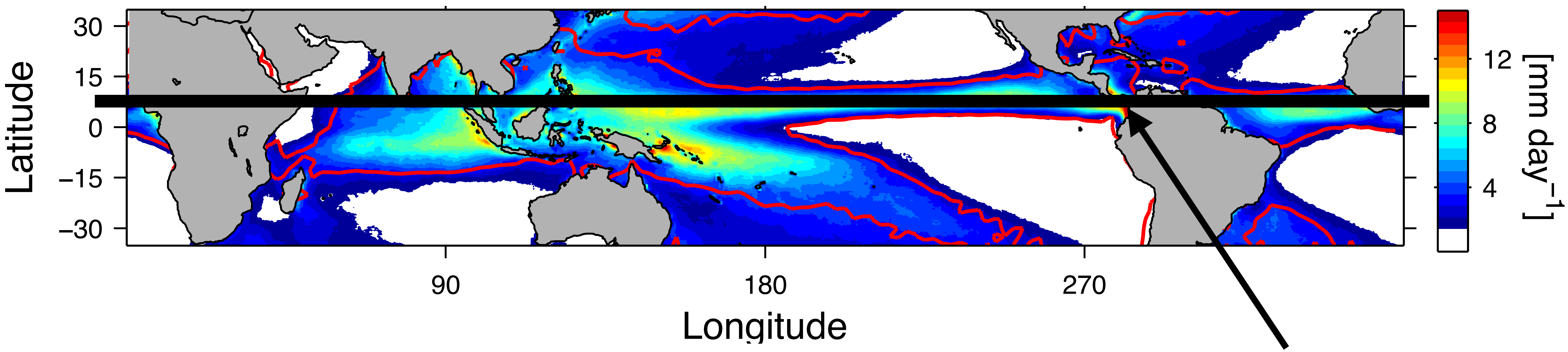
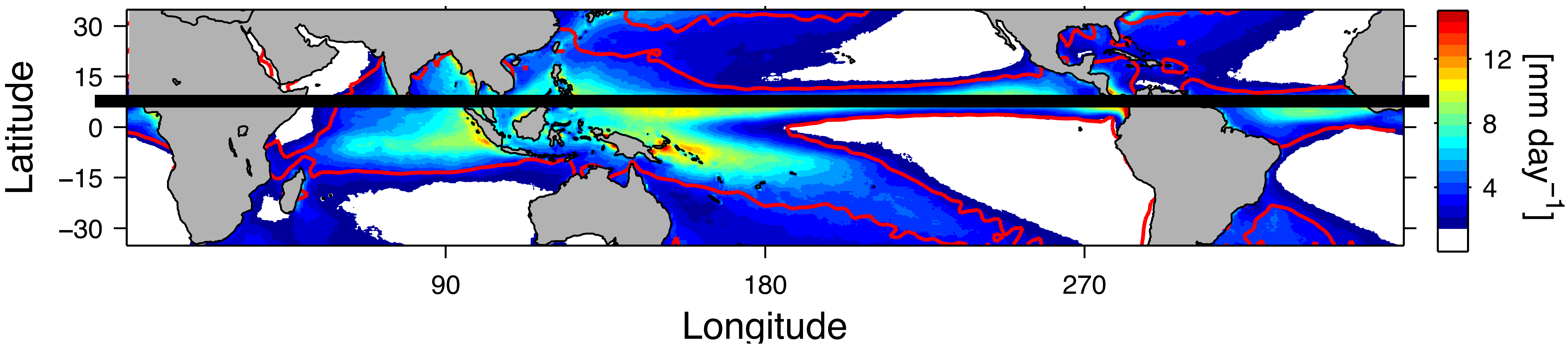
# Intertropical convergence zone




ITCZ lies at ~6degN in zonal & annual mean

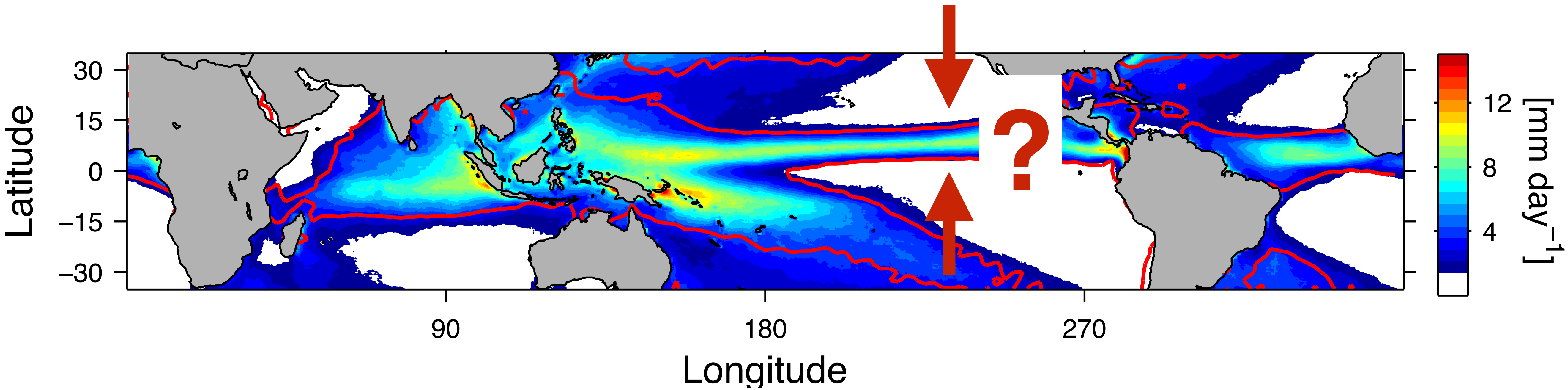
***Colours:*** *TRMM rainfall (1998-2014)*
***Red line:*** *Zero contour of ERA Interim vertical velocity at 700hPa*

# Energetic framework to understand mean ITCZ *latitude*




**ITCZ tends to be in the warmer hemisphere**
(e.g., Kang et al 2008; Marshall et al 2013; Frierson et al 2013; Bischoff & Schneider 2014)

# But what controls the ITCZ *width*?




- Narrowing over last 36 years (Wodzicki & Rapp 2016)
- Influences **regional climate** in the tropics

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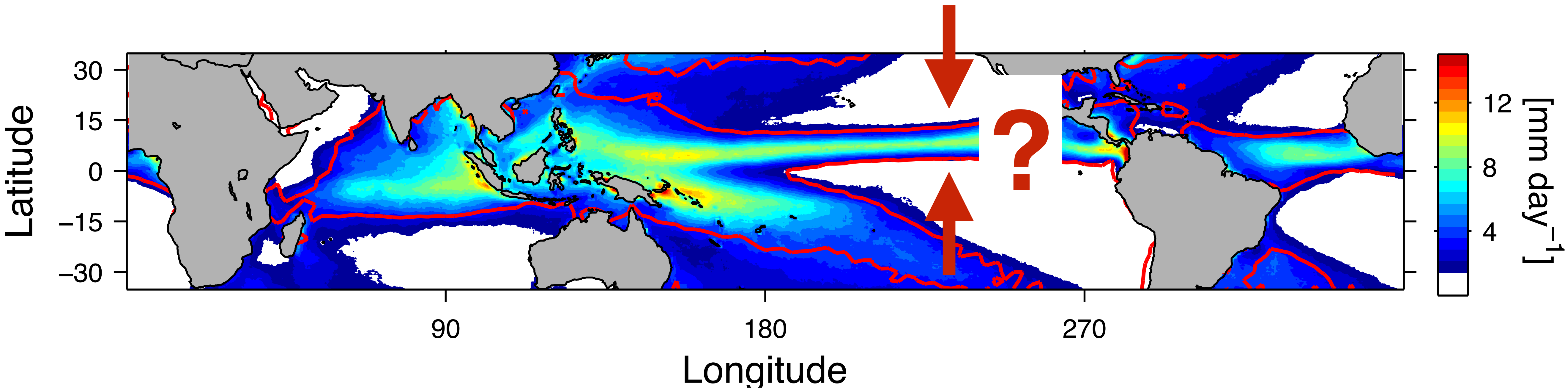



- Narrowing over last 36 years (Wodzicki & Rapp 2016)
- Influences **regional climate** in the tropics
- Potentially important for **climate sensitivity**
  *Pierrehumbert (1995)*: “the warm pool SST is very sensitive to… the relative area of dry versus convective regions.”

# Model hierarchy to investigate ITCZ width

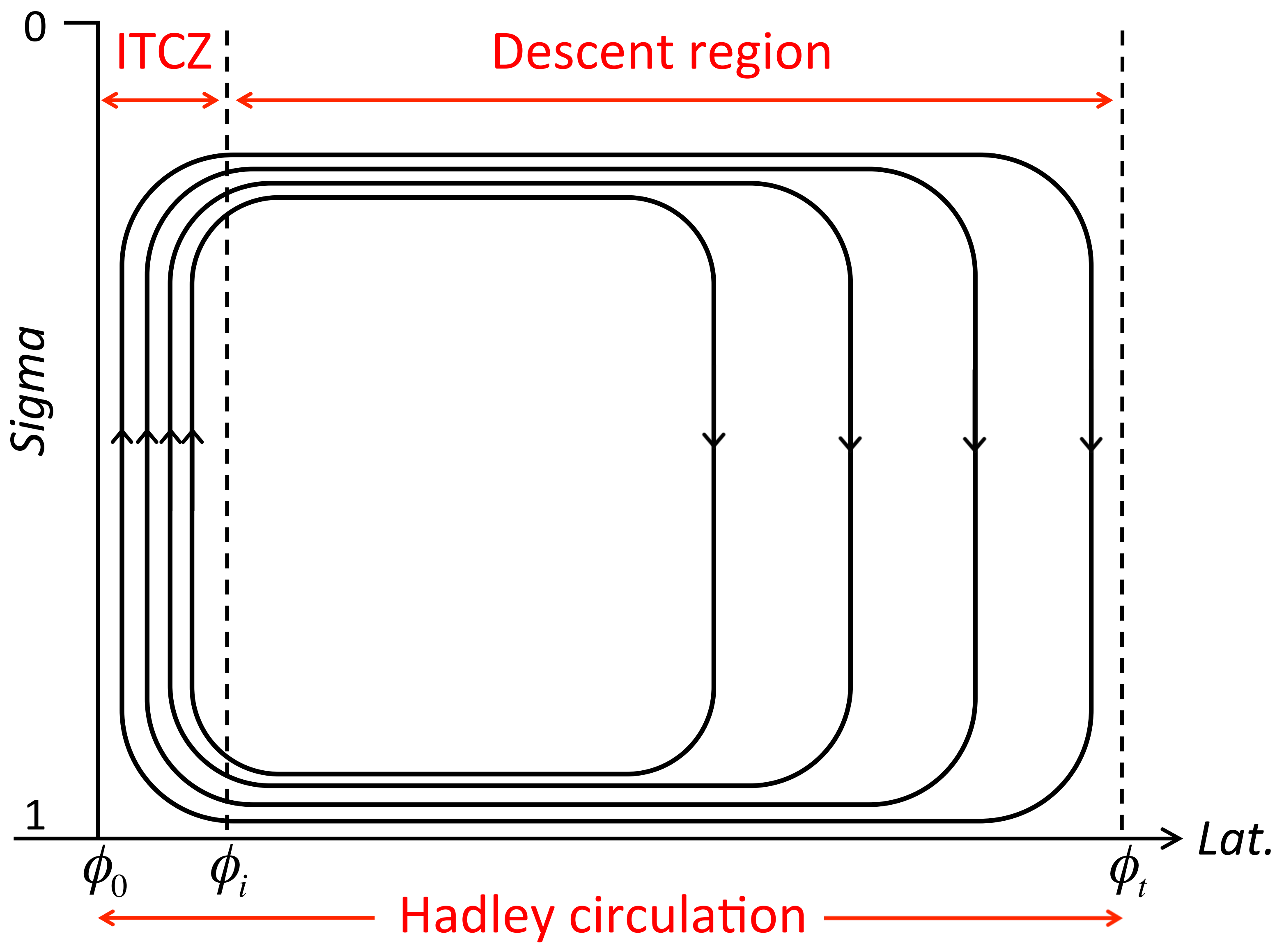
1. Moist, idealised GCM
2. CMIP5 models

# Model hierarchy to investigate ITCZ width

1. Moist, idealised GCM
2. CMIP5 models

3. Analytical, diagnostic model for physical interpretation

# Definition of ITCZ width: upward branch of the zonal-mean Hadley cell



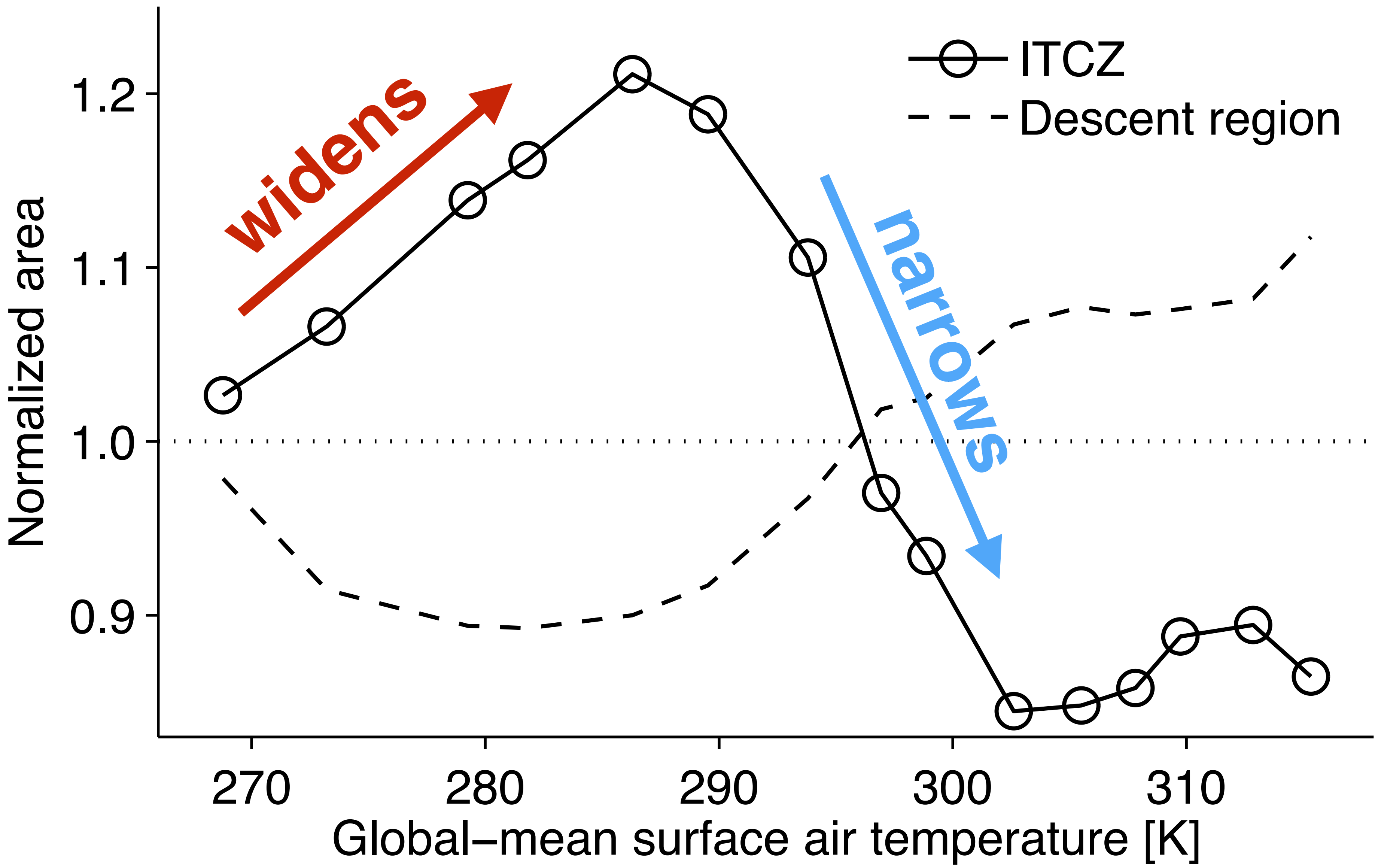

*Byrne & Schneider, J. Climate (2016)*

# Idealised GCM simulations

- Moist, idealised GCM, slab-ocean aquaplanet (Frierson et al 2006; Frierson 2007; O'Gorman & Schneider 2008)
- Perpetual equinox, gray radiation, specified longwave optical thickness, no cloud-radiative or water vapor-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)*

# Diagnostic model for changes in ITCZ width

**Objective:** Derive a diagnostic equation for the sensitivity of ITCZ width to changes in climate

**Method:** Use mass and moist static energy (MSE) budgets of the Hadley cell

*Byrne & Schneider, J. Climate (2016)*

# After some algebra: Sensitivity of the ITCZ width

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

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

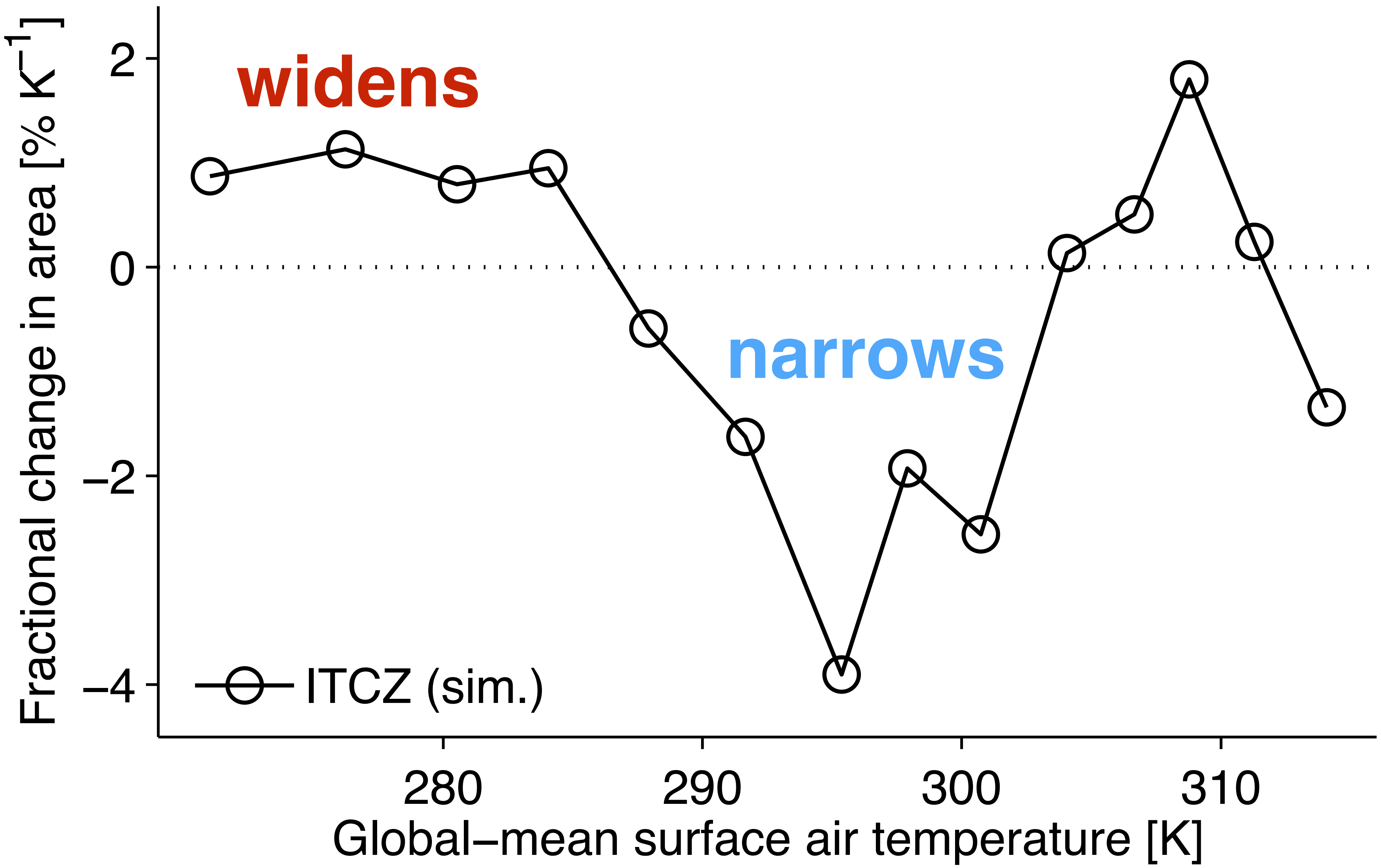
$\delta\mathrm{NEI}+$ ← net energy input to the atmosphere

mean MSE advection → $\delta\mathrm{MeanAdv}+$

$\delta\mathrm{Eddy}$ ← transient-eddy MSE divergence

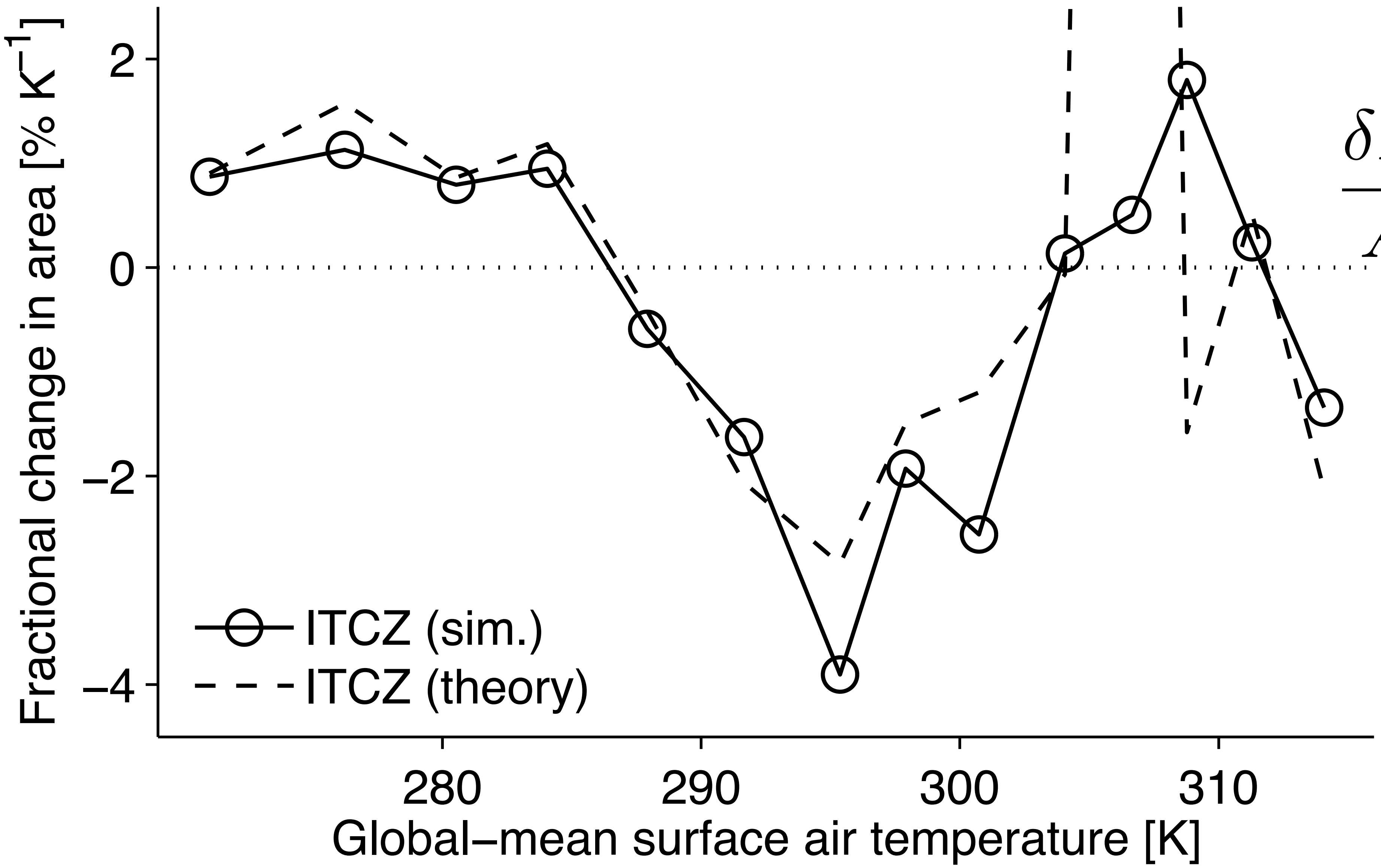
*Byrne & Schneider, J. Climate (2016)*

# Apply diag. model to understand ITCZ width changes in idealised GCM




*Byrne & Schneider, J. Climate (2016)*

# Diag. model 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)*

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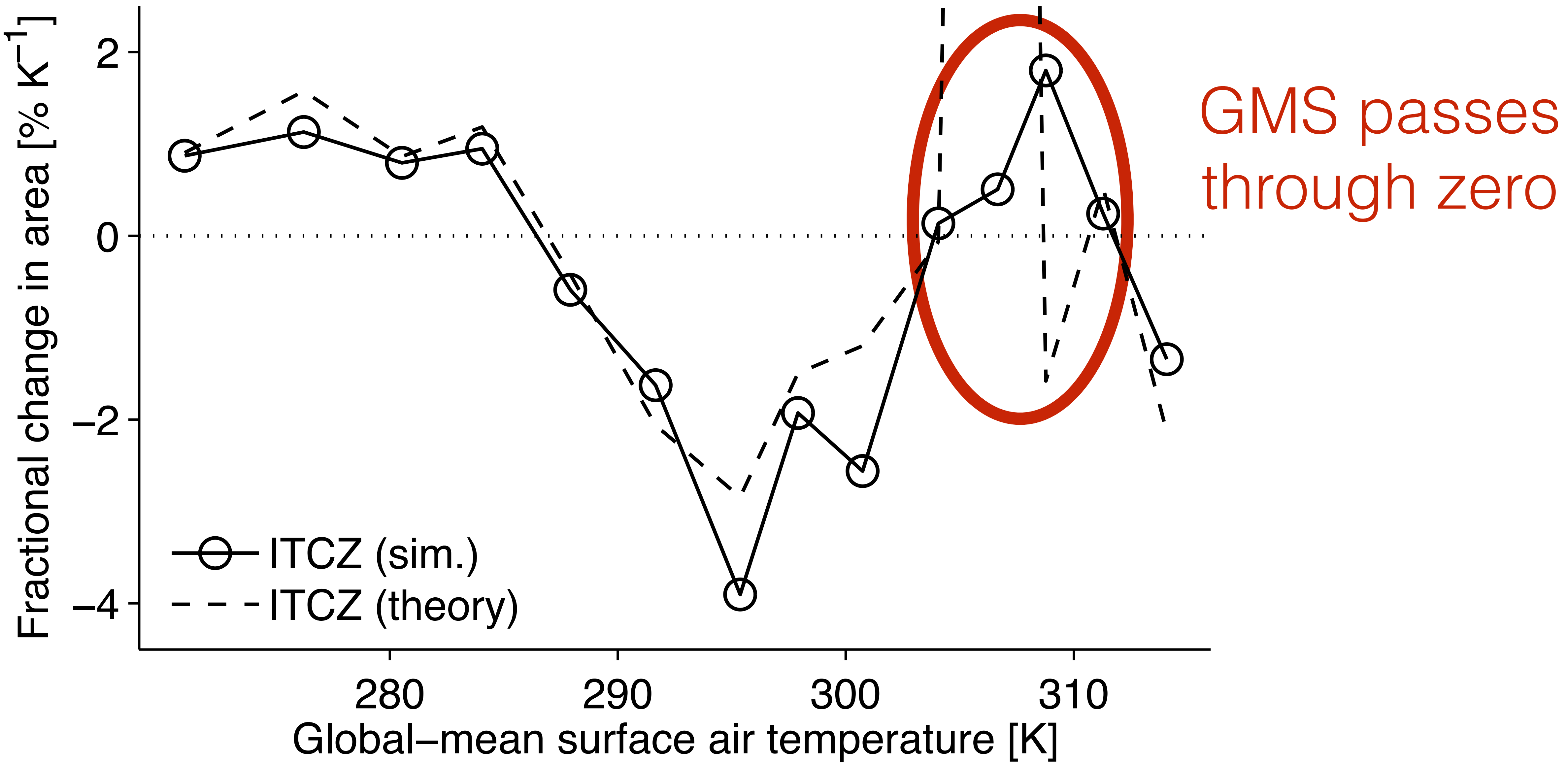
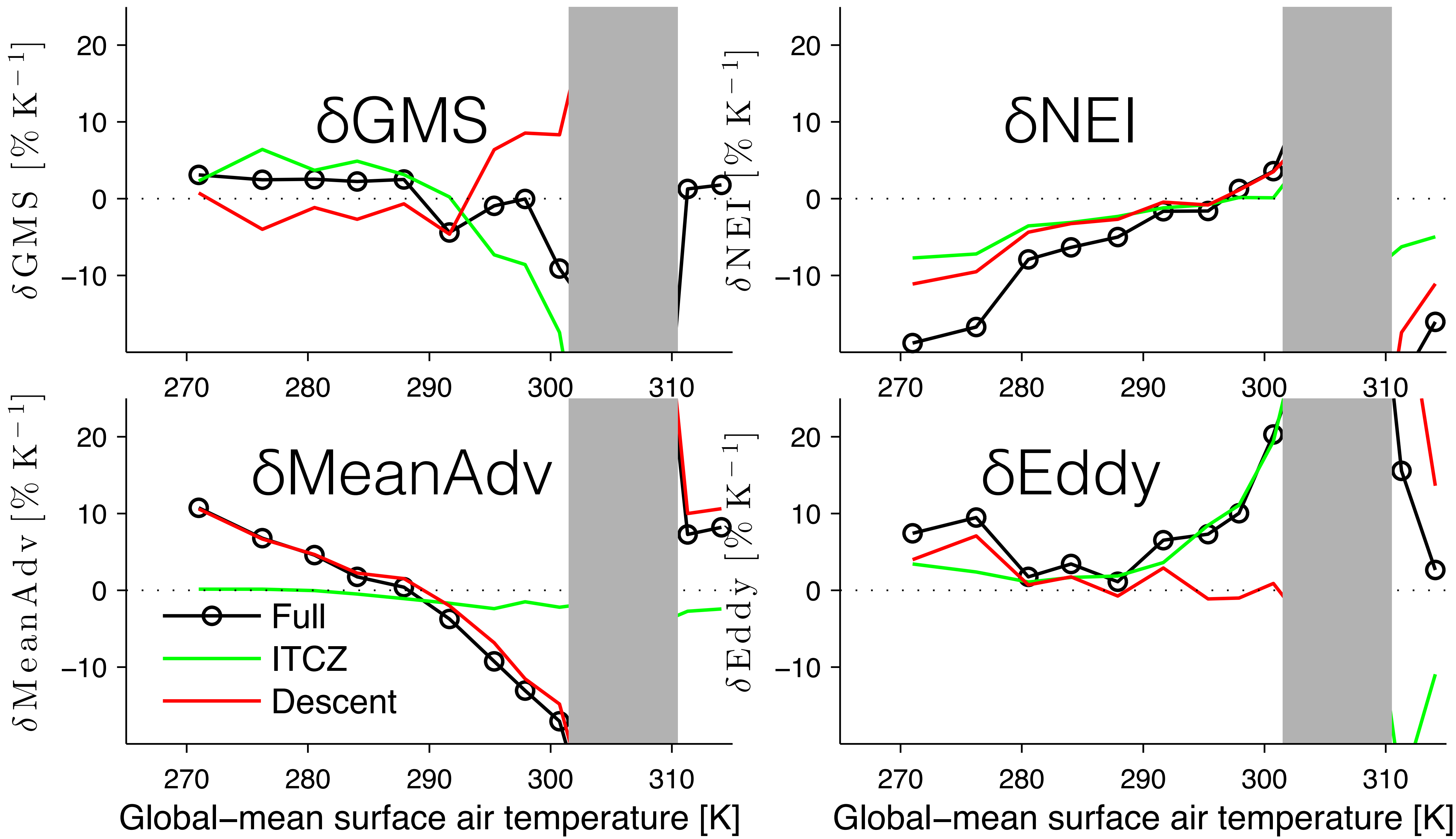


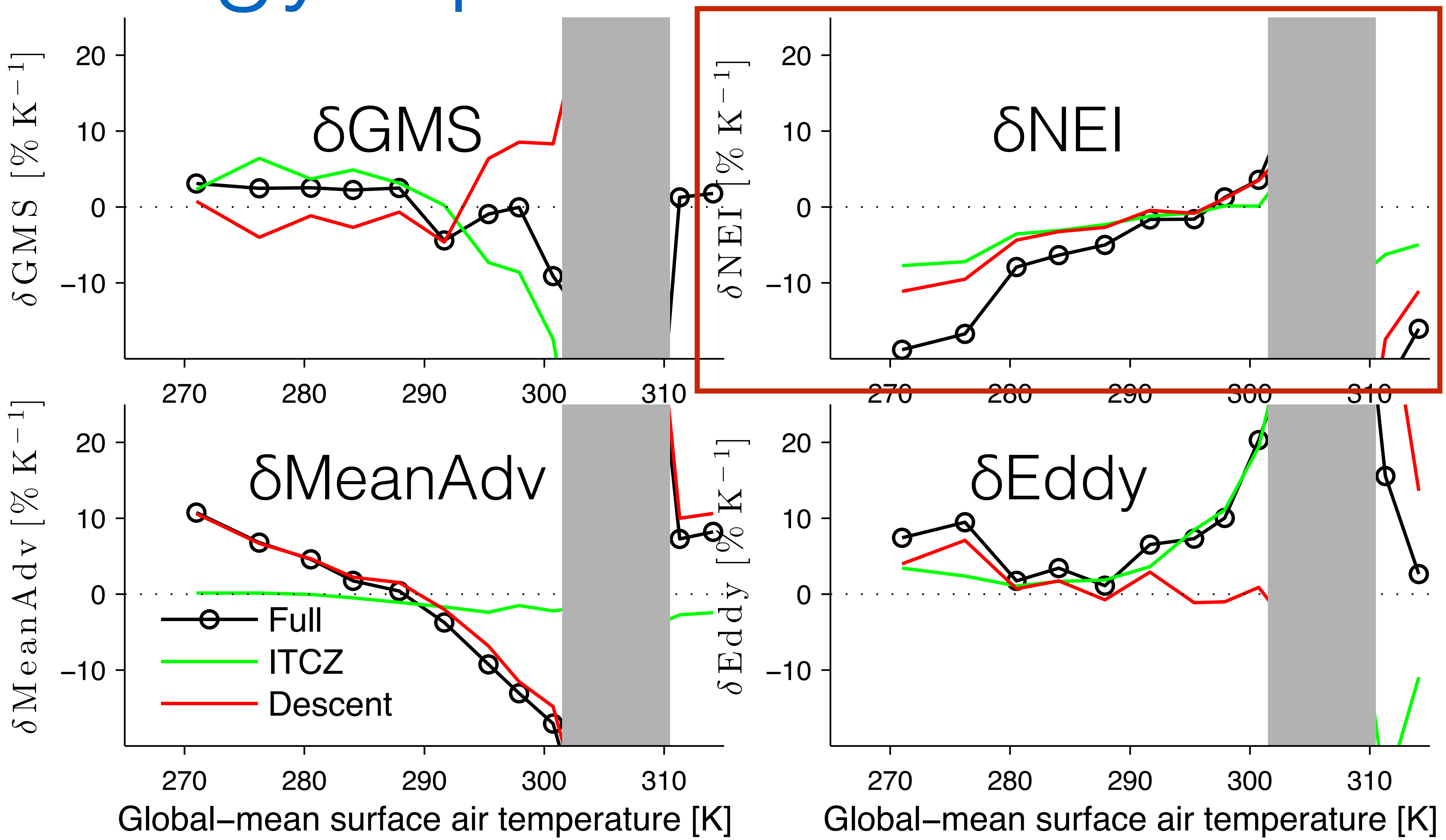

*Byrne & Schneider, J. Climate (2016)*

# 4 contributions to changes in ITCZ width




*Byrne & Schneider, J. Climate (2016)*

# Why do increases in net energy input narrow the ITCZ?

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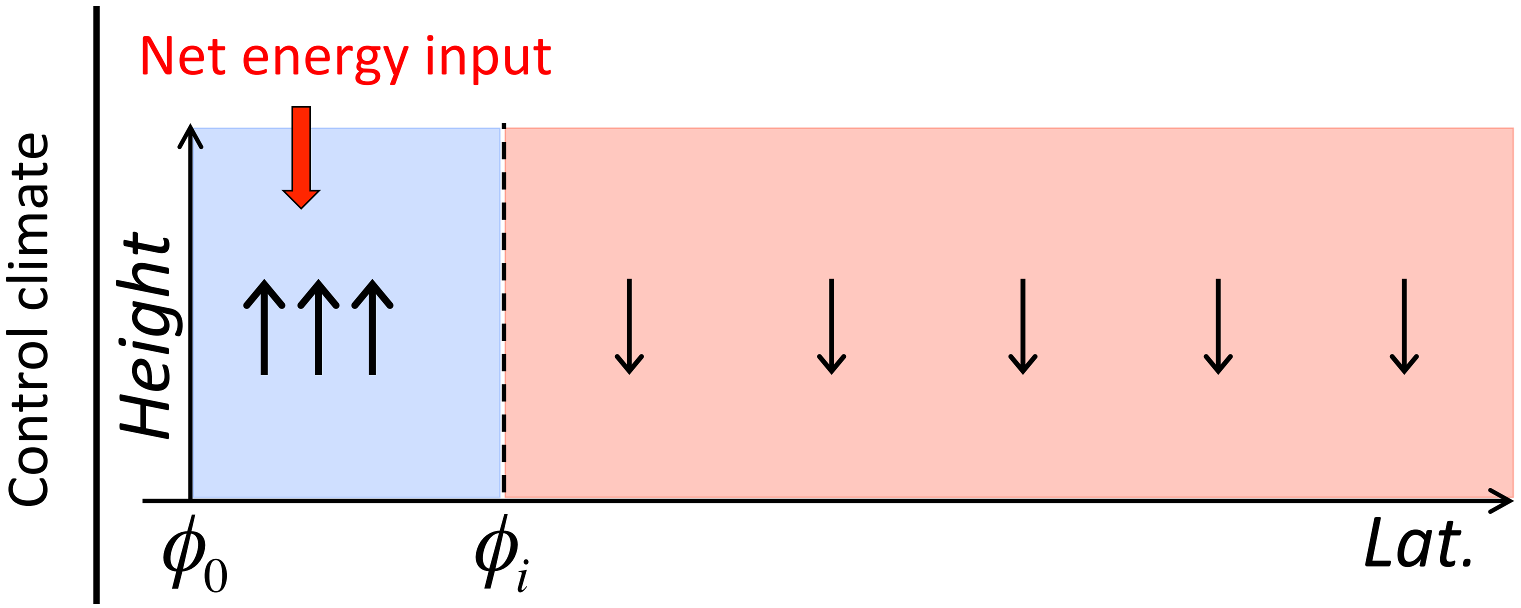


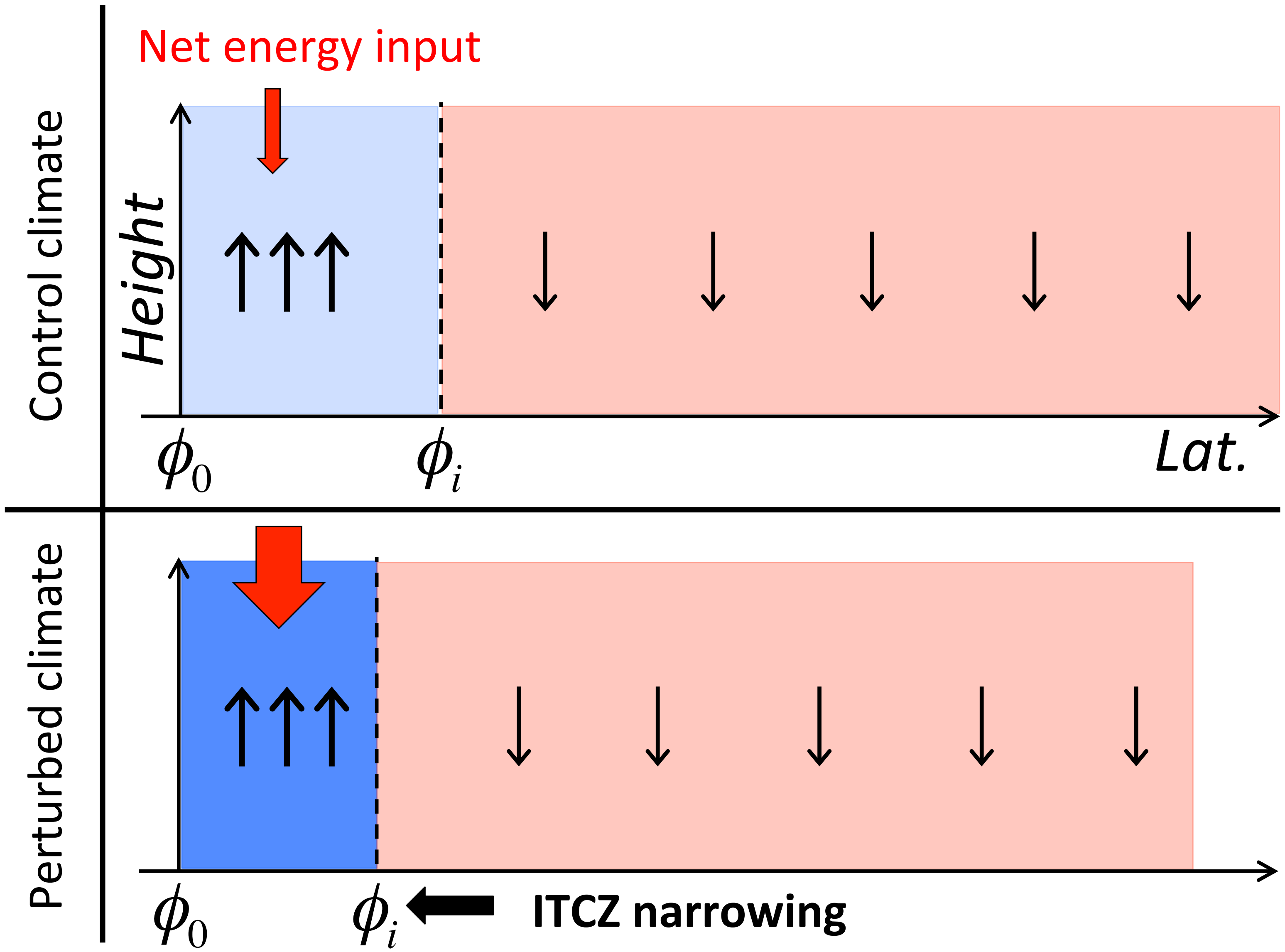

Hadley cell
mass budget

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

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

*Byrne & Schneider, J. Climate (2016)*

# Increase in net energy input balanced by enhanced ascent in ITCZ (all else equal)




Hadley cell mass budget

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

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

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

(for positive GMS)

*Byrne & Schneider, J. Climate (2016)*

# Moving up the model hierarchy: ITCZ width in CMIP5 models

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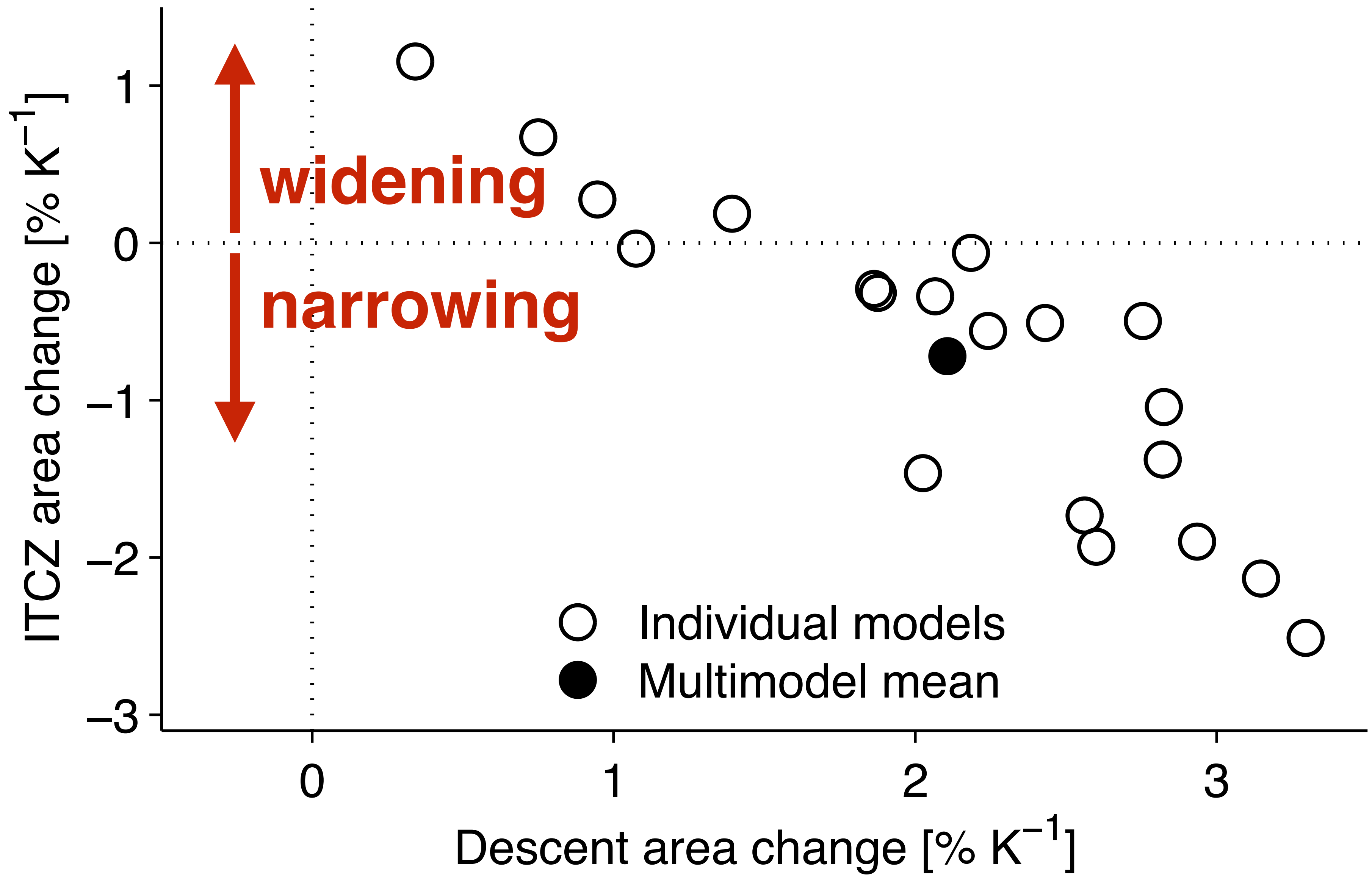
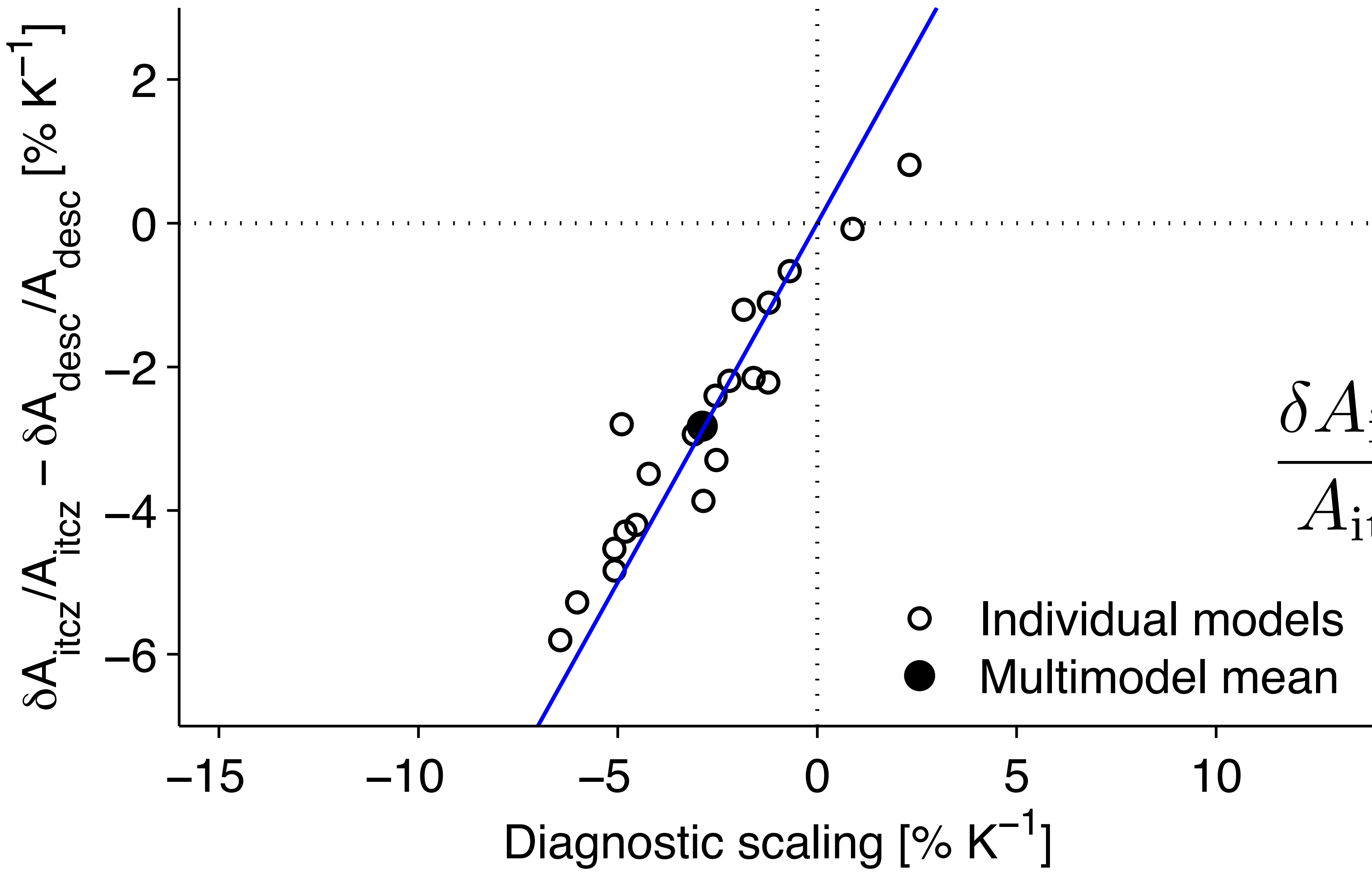



RCP8.5 (2070-2099) - historical (1976-2005)

*Byrne & Schneider, GRL (in press)*

# Why is the ITCZ projected to narrow as the climate warms? Apply diag. model




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

$$\delta \mathrm{GMS} +$$

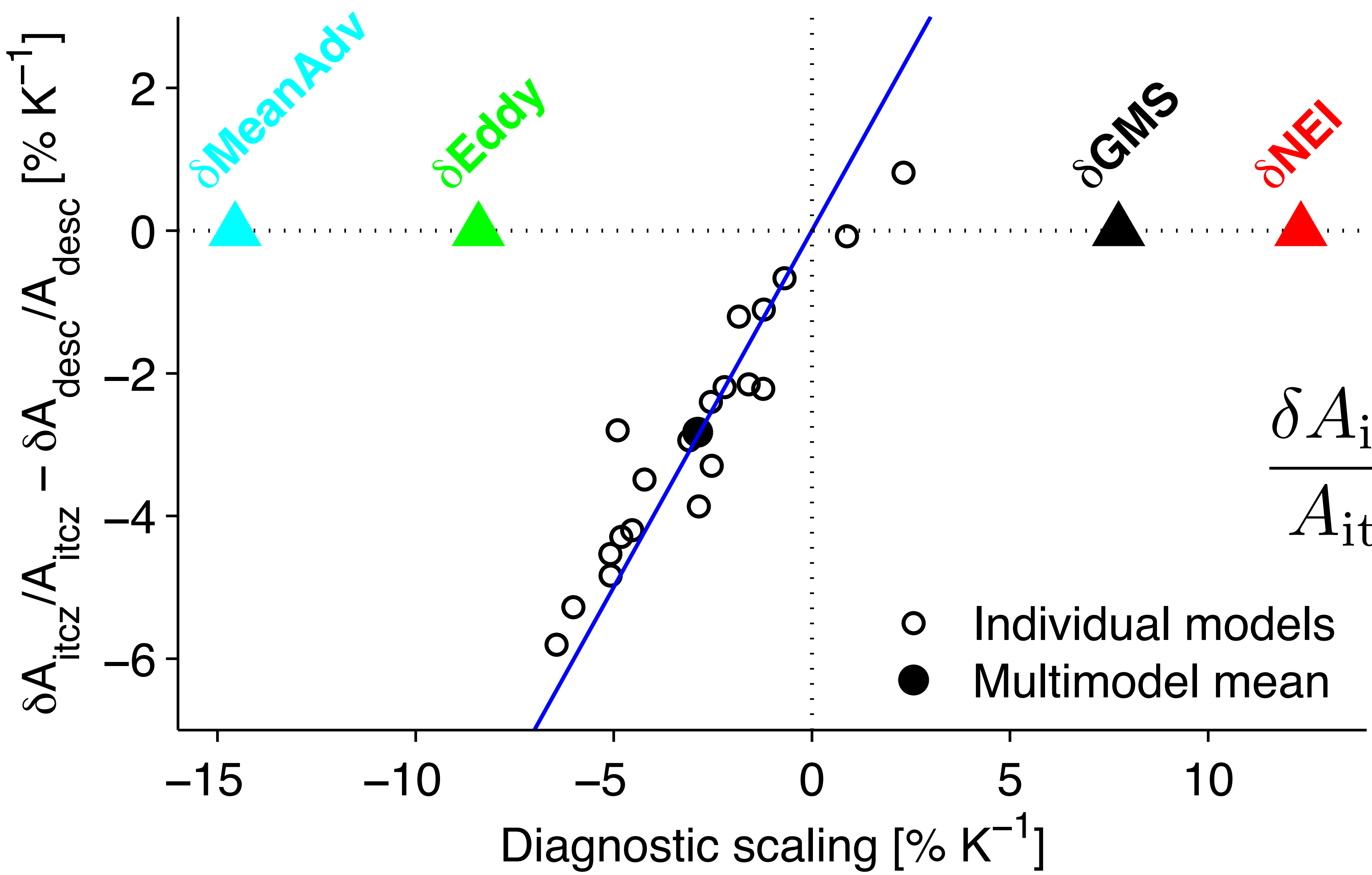
$$\delta \mathrm{NEI} +$$

$$\delta \mathrm{MeanAdv} +$$

$$\delta \mathrm{Eddy}$$

*Byrne & Schneider, GRL (in press)*

# Tug-of-war: Mean advection & eddies *narrow* ITCZ; GMS & net energy input *widen* ITCZ

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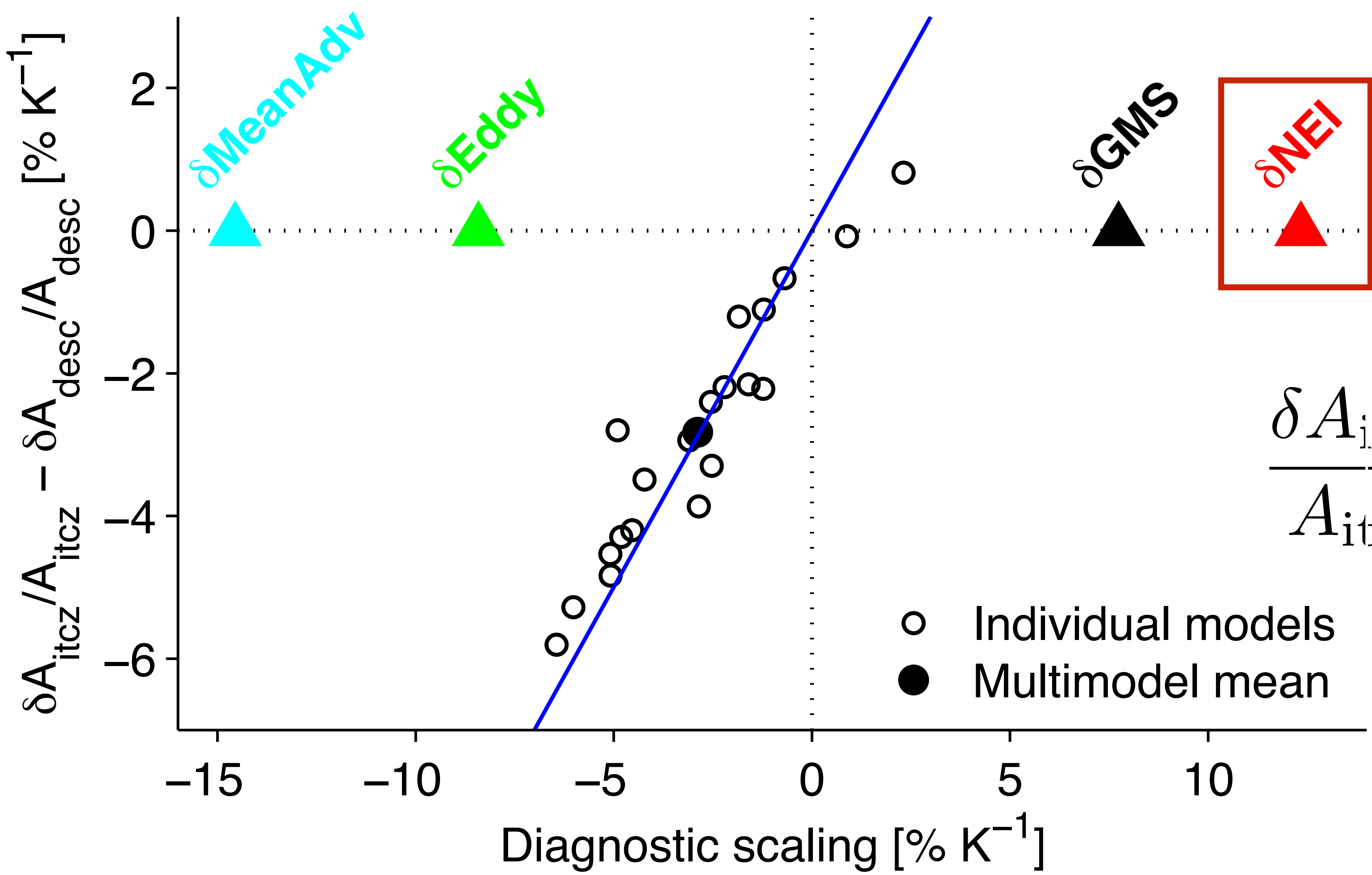
$$\delta\mathrm{Eddy}$$

*Byrne & Schneider, GRL (in press)*

# Net energy input term dominated by shortwave component (clear-sky + cloud effects)

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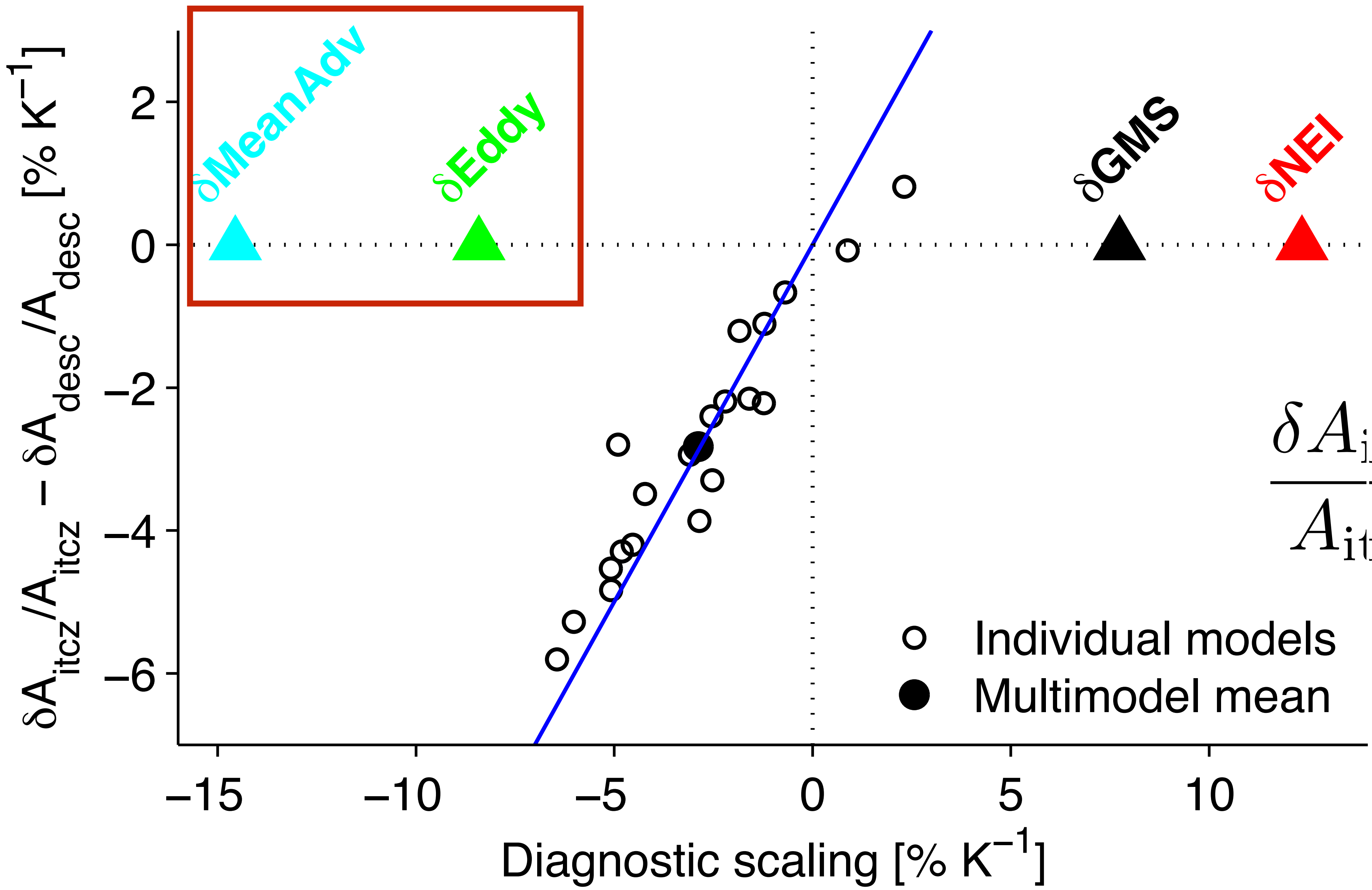
*Byrne & Schneider, GRL (in press)*

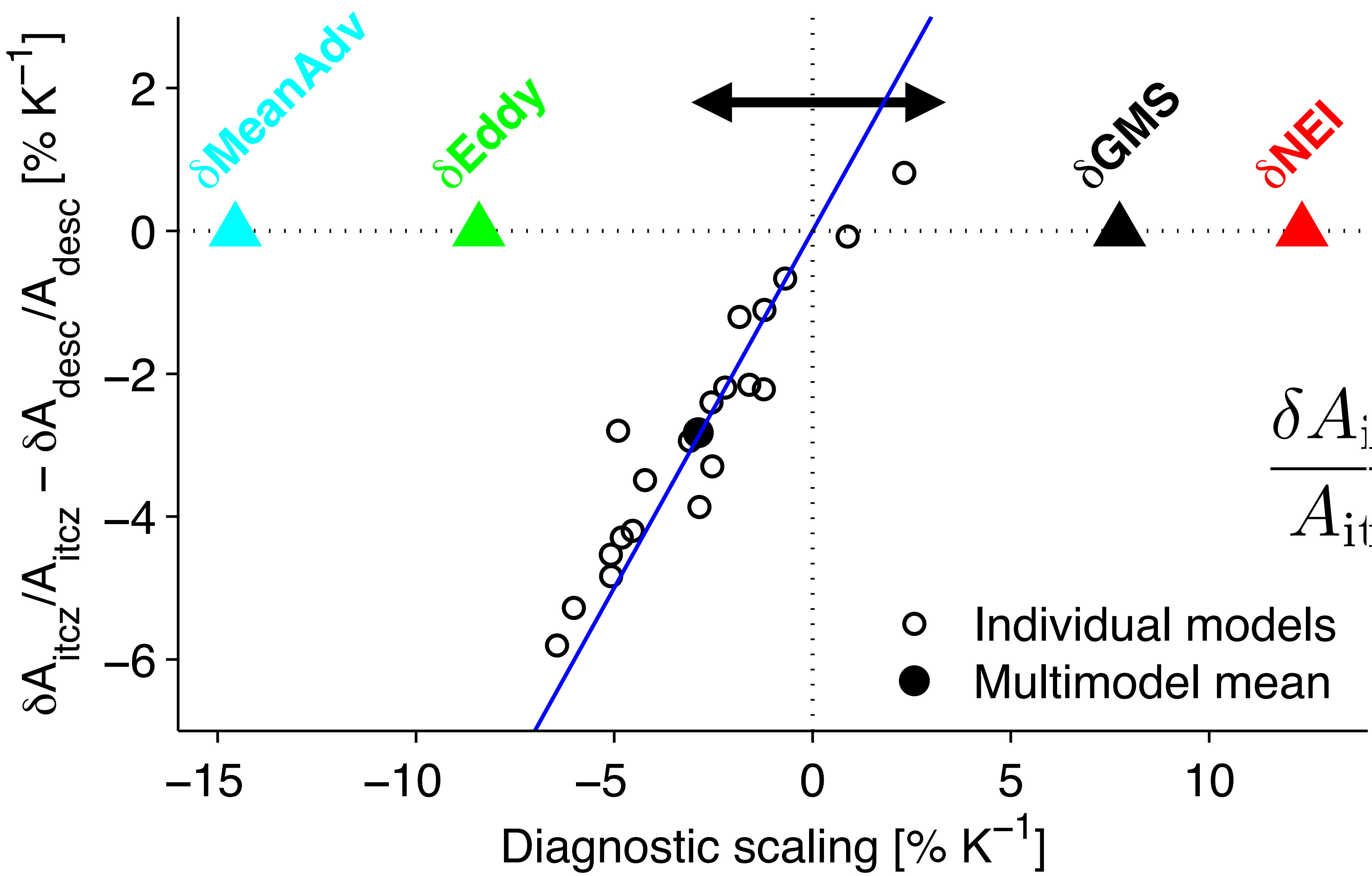
# Narrowing due to increasing meridional MSE gradients




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

*Byrne & Schneider, GRL (in press)*

# Terms have opposite signs to idealised GCM — GMS in ITCZ is *negative* in most CMIP5 models




*Byrne & Schneider, GRL (in press)*

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

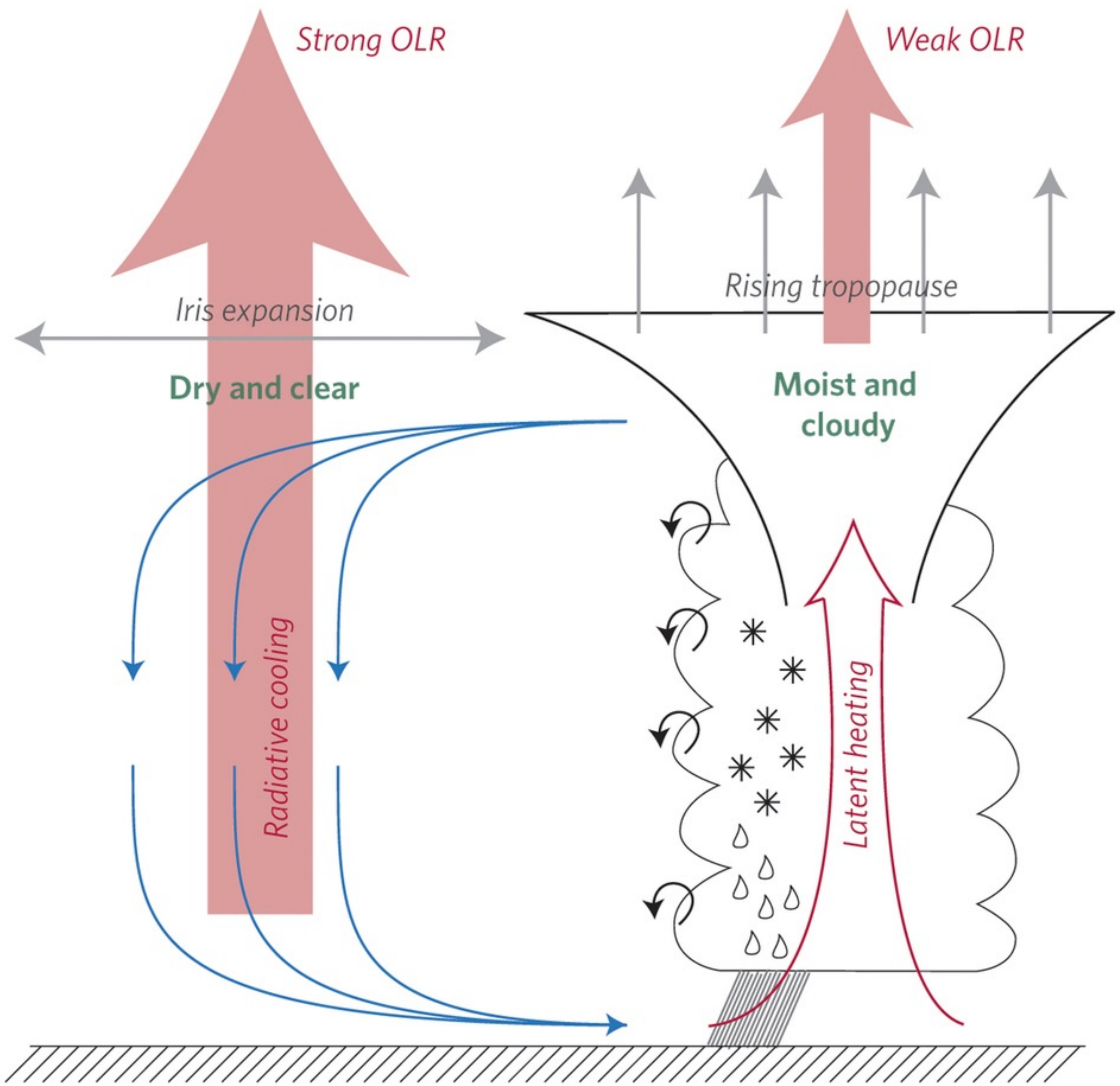
# Summary of physical mechanisms in CMIP5 models

- *Processes that widen the ITCZ:*
  - Increased shortwave absorption in a warmer climate (cloud & clear-sky effects)
  - Changes in GMS

- *Processes that narrow the ITCZ:*
  - Larger meridional MSE gradient -> increased cooling of the ITCZ by mean advection and transient eddies

*Byrne & Schneider, GRL (in press)*

# ITCZ narrowing and climate sensitivity: A GCM-resolved 'iris' effect?

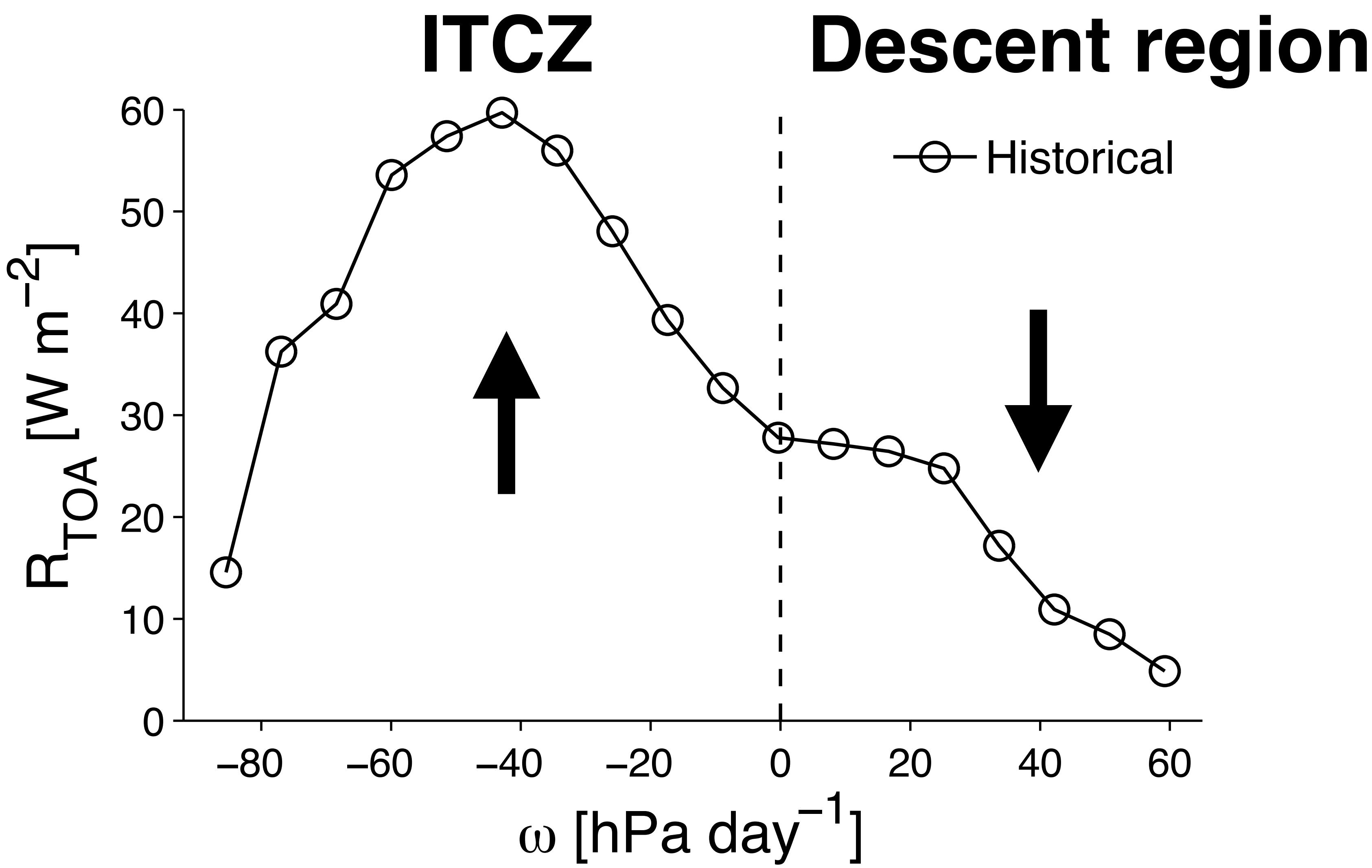



*Mauritsen & Stevens (2015)*

# Net TOA heating as a function of circulation regime

$$R_{\mathrm{TOA}} = SW\downarrow - SW\uparrow - LW\uparrow$$

Historical (1976-2005), lat= -40,40




*following Bony et al (2004)*

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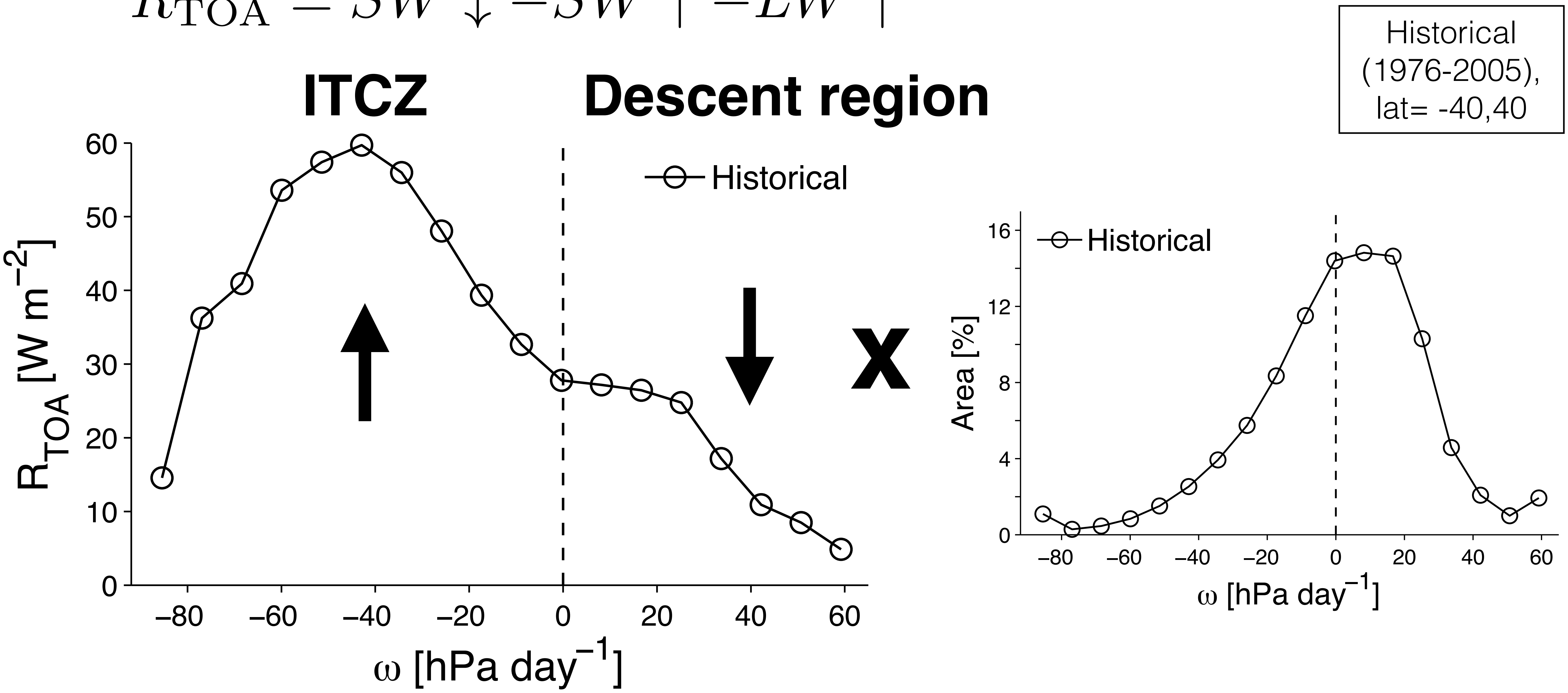



*following Bony et al (2004)*

# Average changes in net TOA heating as a function of thermodynamic and dynamic components

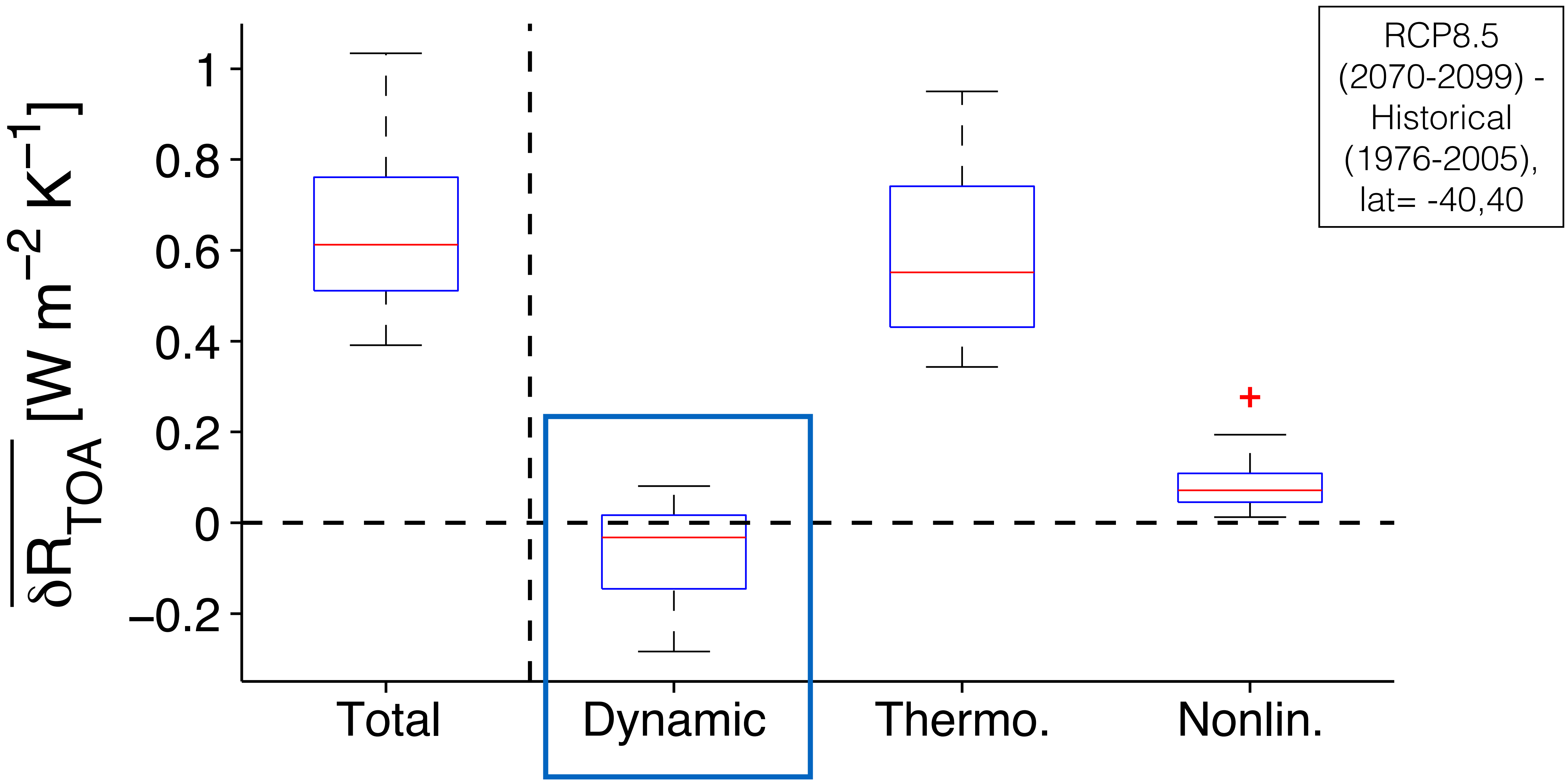
$$\overline{\delta R_{\mathrm{TOA}}} = \int_{-\infty}^{\infty} R_{\mathrm{TOA}}(\omega)\delta A(\omega)d\omega + \int_{-\infty}^{\infty} \delta R_{\mathrm{TOA}}(\omega)A(\omega)d\omega$$

↑ dynamic component (first term)

↑ thermodynamic component (second term)

*following Bony et al (2004)*

# Tropical circulation changes are a negative feedback on climate change — a GCM-resolved ‘iris’ effect



# Summary

1. ITCZ widens & narrows as the climate warms in idealised simulations; narrows in most CMIP5 models
2. Diagnostic model to understand physical mechanisms — relevant for convective aggregation in RCE?

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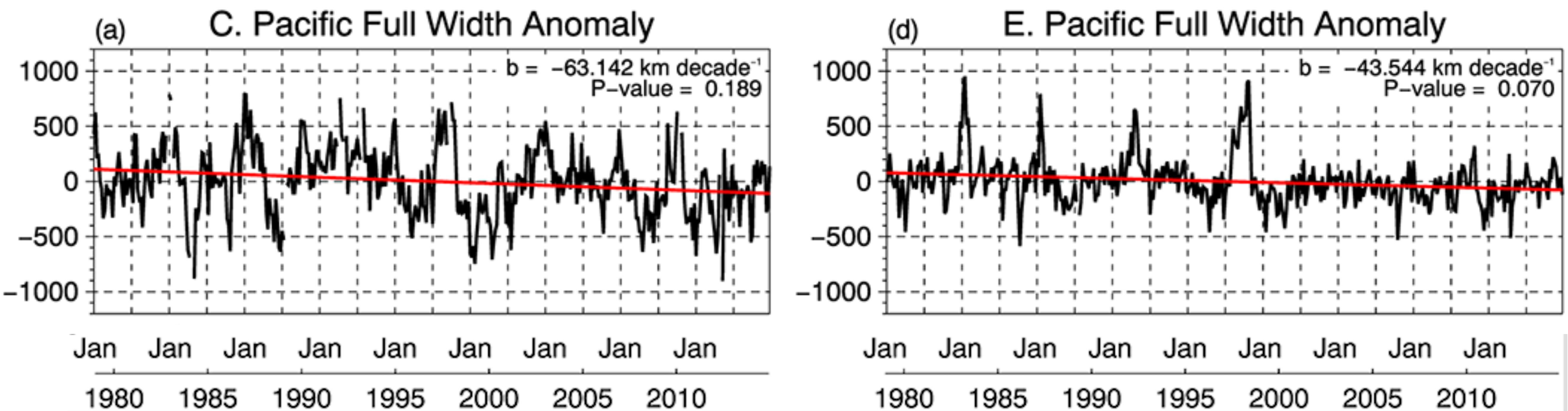
1. ITCZ widens & narrows as the climate warms in idealised simulations; narrows in most CMIP5 models
2. Diagnostic model to understand physical mechanisms — relevant for convective aggregation in RCE?
3. ‘Tug-of-war’ between increasing meridional MSE gradients and shortwave absorption. Strongly depends on gross moist stability in ITCZ
4. A GCM-resolved ‘iris’ effect due to tropical circulation changes

# Extra slides

# Pacific ITCZ has narrowed in recent decades




- Significant narrowing of ITCZ over last 36 years (Wodzicki & Rapp 2016)

# Diagnostic model for the ITCZ width

**Hadley cell mass budget:**

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

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

**Atmospheric energy budget:**

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

net energy input ("NEI")

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

Mean divergent flow

Mean advection

Trans. eddies

*Byrne & Schneider, J. Climate (2016)*

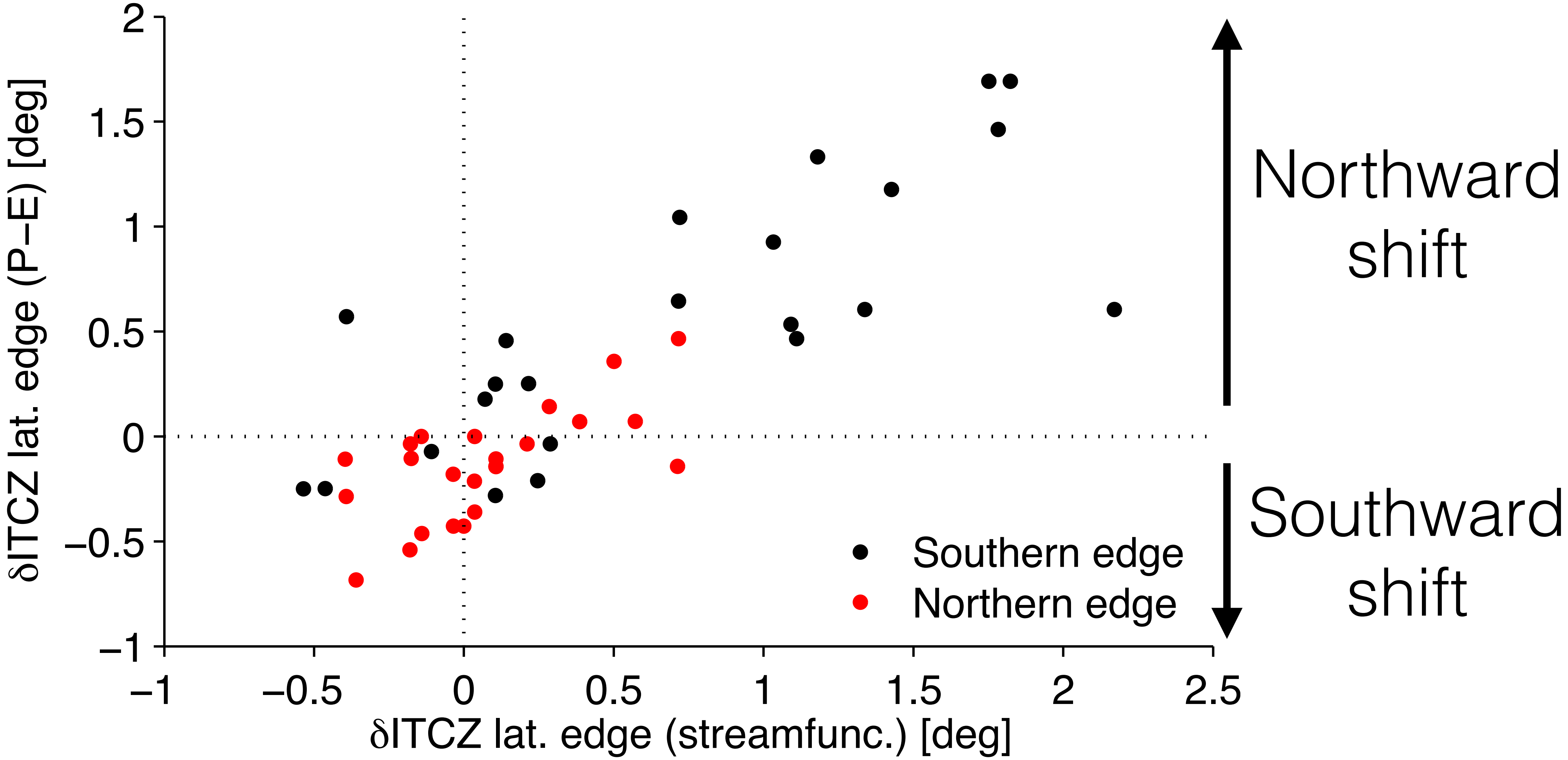
# Linearise: Sensitivity of the ITCZ width

$$\frac{\delta A_{\mathrm{itcz}}}{A_{\mathrm{itcz}}} - \frac{\delta A_{\mathrm{desc}}}{A_{\mathrm{desc}}} = \frac{\delta(\Delta h_{\mathrm{itcz}})}{\Delta h_{\mathrm{itcz}}} - \frac{\delta(\Delta h_{\mathrm{desc}})}{\Delta h_{\mathrm{desc}}} + \frac{1}{H_{\mathrm{itcz}}}\left[\delta\langle\overline{S}-\overline{L}-\overline{O}\rangle_{\mathrm{desc}}\frac{H_{\mathrm{itcz}}}{H_{\mathrm{desc}}} - \delta\langle\overline{S}-\overline{L}-\overline{O}\rangle_{\mathrm{itcz}}\right] - \frac{1}{H_{\mathrm{itcz}}}\left[\delta\langle\{\overline{v}\cdot\nabla\overline{h}\}\rangle_{\mathrm{desc}}\frac{H_{\mathrm{itcz}}}{H_{\mathrm{desc}}} - \delta\langle\{\overline{v}\cdot\nabla\overline{h}\}\rangle_{\mathrm{itcz}}\right] - \frac{1}{H_{\mathrm{itcz}}}\left[\delta\langle\{\nabla\cdot\overline{v'h'}\}\rangle_{\mathrm{desc}}\frac{H_{\mathrm{itcz}}}{H_{\mathrm{desc}}} - \delta\langle\{\nabla\cdot\overline{v'h'}\}\rangle_{\mathrm{itcz}}\right]$$

$$H_{\mathrm{itcz}} \equiv -\Delta h_{\mathrm{itcz}}\omega_{\mathrm{itcz}}/g$$
$$H_{\mathrm{desc}} \equiv -\Delta h_{\mathrm{desc}}\omega_{\mathrm{desc}}/g$$

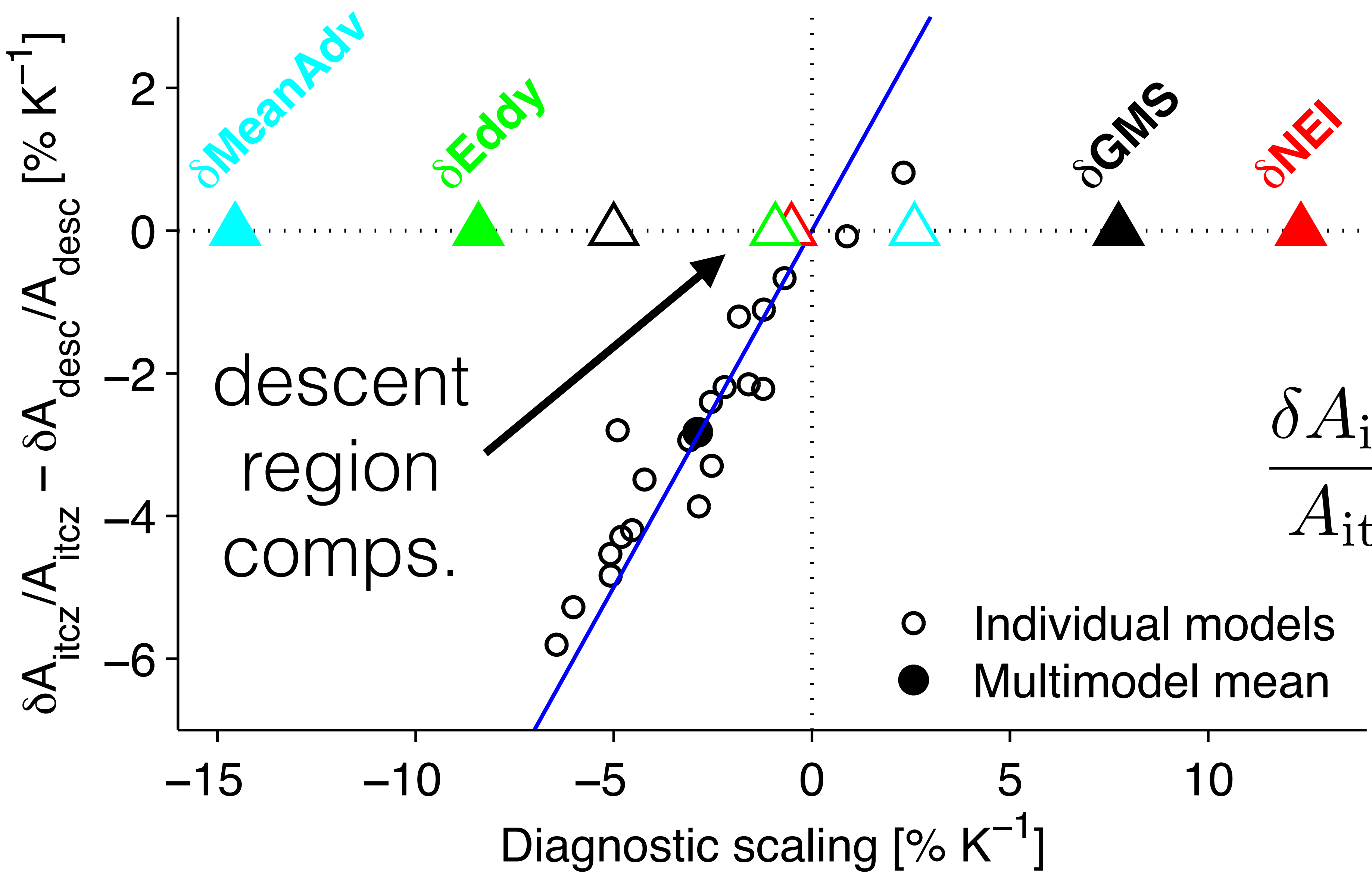
*Byrne & Schneider, J. Climate (2016)*

# Narrowing mostly due to northward shift of southern edge of the ITCZ




*Byrne & Schneider (in preparation)*

# Energetics within ITCZ dominate width changes

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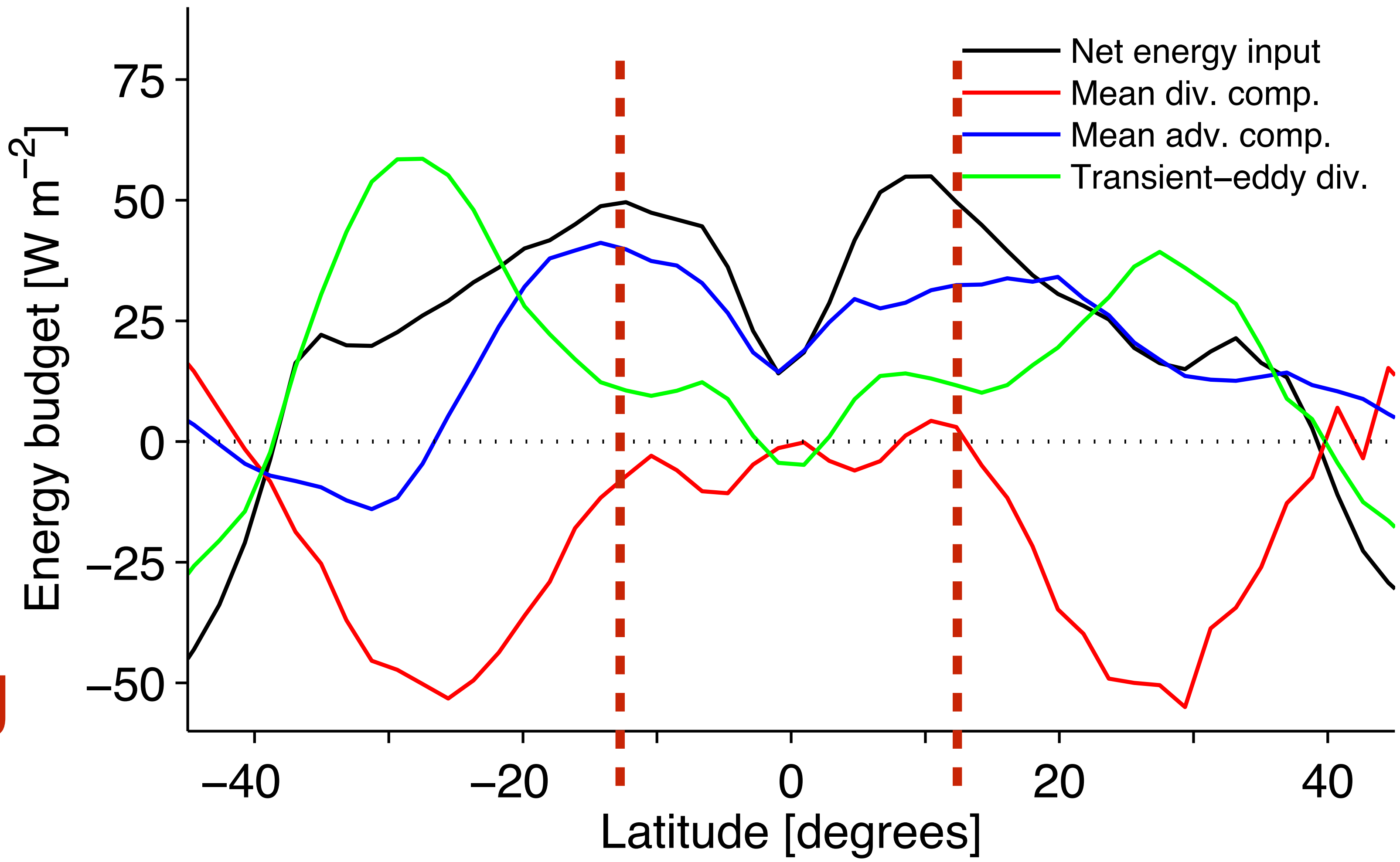
*Byrne & Schneider, GRL (in press)*

# Physical interpretation: Atmospheric energy budget in ITCZ




IPSL-CM5A-LR:
Historical simulation
(1976-2005)

**warming terms**

**cooling terms**

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

*Byrne & Schneider, GRL (in press)*

# How does net TOA heating change with warming? Thermodynamic & dynamic components