Dynamic and energetic constraints on the modality and position of the intertropical convergence zone in an aquaplanet

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Motivation

The zonal mean tropical atmospheric circulation, generally known as the Hadley circulation, is characterized by ascent over an intertropical convergence zone (ITCZ) and descent in the subtropics. The mean atmospheric circulation is roughly paralleled by the underlying wind-driven ocean circulation, with equatorial upwelling, and downwelling at higher latitudes. The partitioning of energy transport between the atmospheric tropical overturning circulation and its oceanic counterpart has a critical role in setting the properties of the Hadley circulation and of the mean tropical precipitation.

In the two papers listed above, we study the effect of wind-driven ocean energy transport on shifts of the ITCZ and on the emergence of double ITCZs. The dynamics of the ITCZ are studied using an idealized atmospheric model coupled to a slab ocean with parameterized Ekman energy transport. Unlike previous studies, the parameterized cross-equatorial ocean energy transport, which is critical for the coupled response, is explicitly represented as the curl of the wind stress at the equator.

Ekman Energy Transport in an Idealized GCM

Idealized GCM

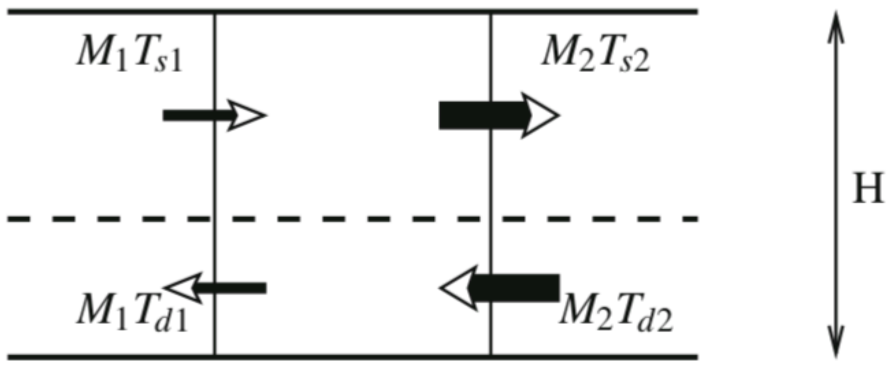
Frierson/Schneider/O'Gorman stripped-down version of the GFDL model

Ekman energy transport

1.5-layer Codron (2012) scheme

$$\nabla \cdot F^{Ek} = -\frac{C}{a\ \cos(\phi)}\frac{\partial}{\partial \phi}\left(M_y(T_s - T_d)\cos(\phi)\right)$$

$$M_y = \frac{-f\tau_x + \varepsilon^2 \frac{\hat{k}\cdot(\vec{\nabla}\times\vec{\tau})}{\beta_o}}{f^2 + \varepsilon^2}$$



F^{Ek} = wind-driven ocean energy transport

$T_s - T_d$ = Difference between surface and 'deep' return currents

Ekman mass flux

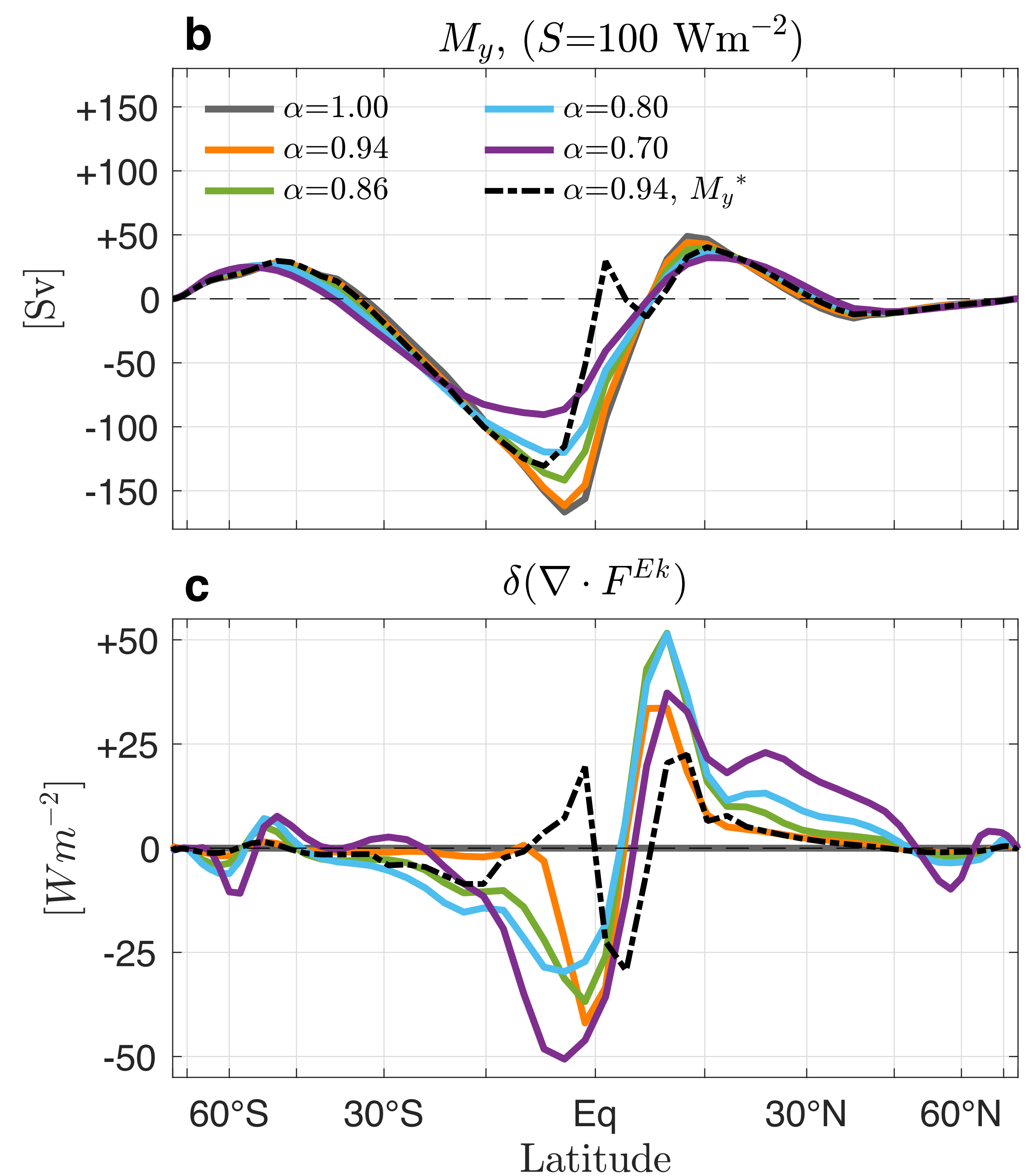
- Novel representation explicitly resolves cross-equatorial fluxes

O'Gorman, P. A., and T. Schneider, 2008: The hydrological cycle over a wide range of climates simulated with an idealized GCM. *J. Climate*, **21**, 3815-3832

Codron F., 2012: Ekman heat transport for slab oceans. *Clim. Dyn.* (38) 379-389

Key model parameters:

1. α = ocean stratification
    - $T_s - T_d = 0$ for $\alpha = 1$
    - $T_s - T_d$ increases as $\alpha \to 0$
2. Hemispherically asymmetric heating amplitude S



Advantage of the new scheme:

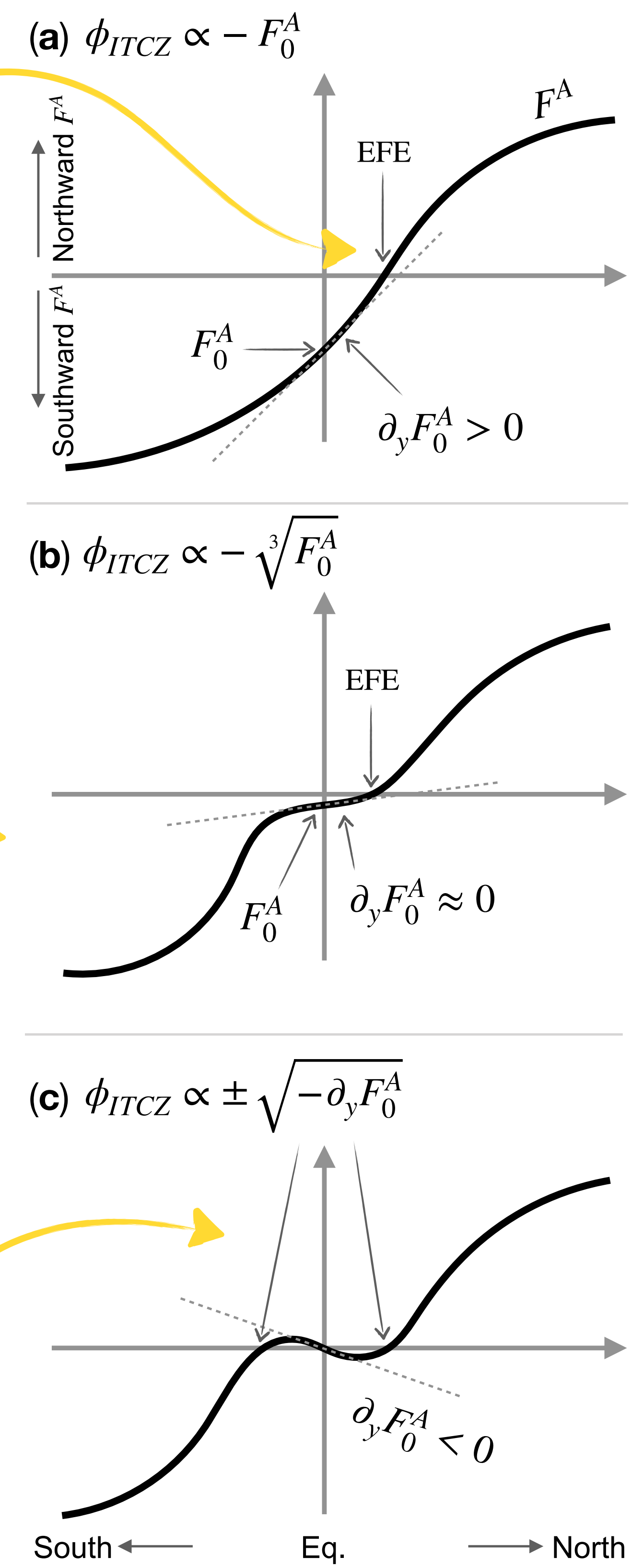
Explicitly resolves cross-equatorial ocean energy transport, allowing the study of the coupled response to asymmetric heating in an idealized setting.

Theory

The ITCZ covaries with the energy flux equator (EFE) of the atmosphere, where meridional atmospheric energy transport F^A vanishes

The gradient of the atmospheric energy transport at the equator $\partial_y F_0^A$ sets the dependence of the ITCZ on asymmetric heating.

When the gradient of the atmospheric energy transport near the equator turns negative ($\partial_y F_0^A < 0$), F^A has more than one root, causing the emergence of a 'double-ITCZ' (more than one EFE)



Bischoff, T., Schneider, T., 2014: Energetic constraints on the position of the intertropical convergence zone. *J. Climate* **27**, 4937–4951

Bischoff, T., Schneider, T., 2016: The equatorial energy balance, ITCZ position, and double-ITCZ bifurcations. *J. Climate*, **29**, 2997–3013

Adam, O., T. Bischoff & T. Schneider, 2016: Seasonal and interannual variations of the energy flux equator and ITCZ. Part I: Zonally averaged ITCZ position. *J. Climate*, **29**, 3219-3230

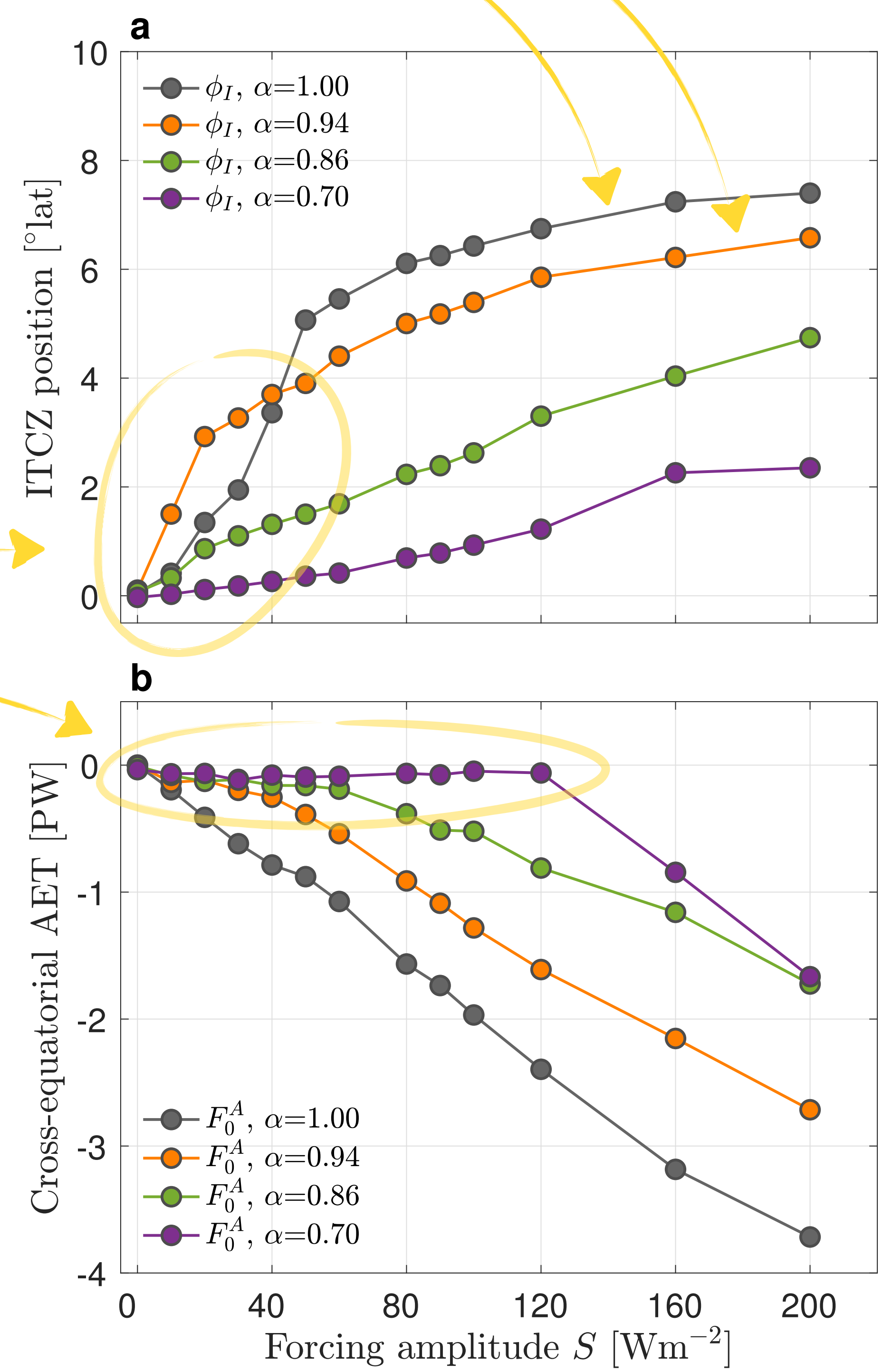
Adam, O., Bischoff, T., Schneider, T., 2016: Seasonal and interannual variations of the energy flux equator and ITCZ. Part II: zonally varying shifts of the ITCZ. *J. Climate* **29**, 7281–7293

Results - Afargan and Adam 2020

1. Damped response of the ITCZ to asymmetric heating, for sufficiently strong asymmetric heating (as previously shown by, e.g., Green and Marshall, 2017).

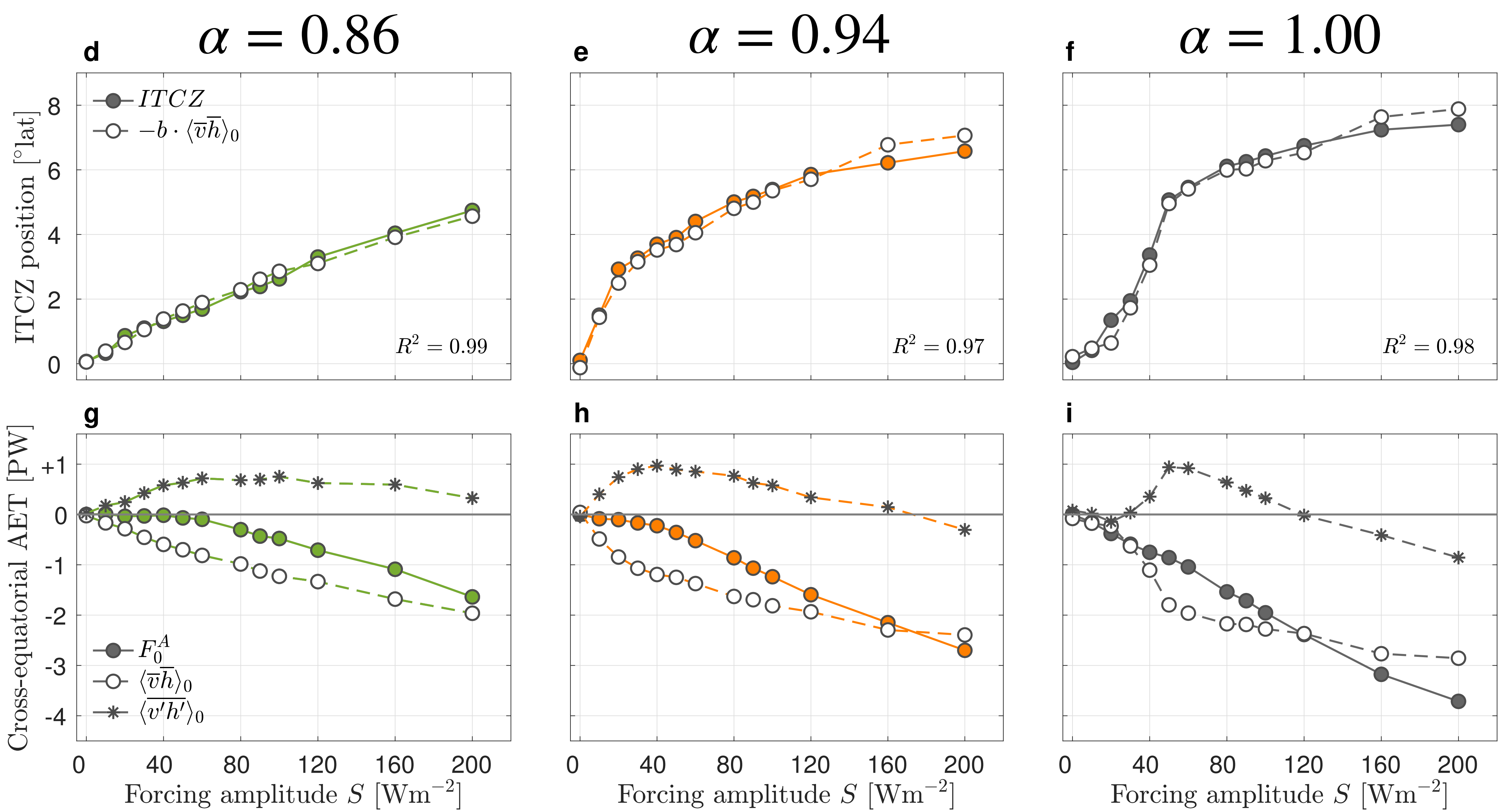
2. Nonlinear response for weak asymmetric heating

3. For sufficiently strong ocean stratification, cross-equatorial atmospheric energy transport nearly vanishes (i.e., nearly all of the cross-equatorial energy transport is done by the wind-driven ocean energy transport). In this case, shifts of the ITCZ appear to be inconsistent with theory.



Green, B., & Marshall, J., 2017: Coupling of trade winds with ocean circulation damps ITCZ shifts. *Journal of Climate*, *30*(12), 4395–4411

Results - Afargan and Adam 2020

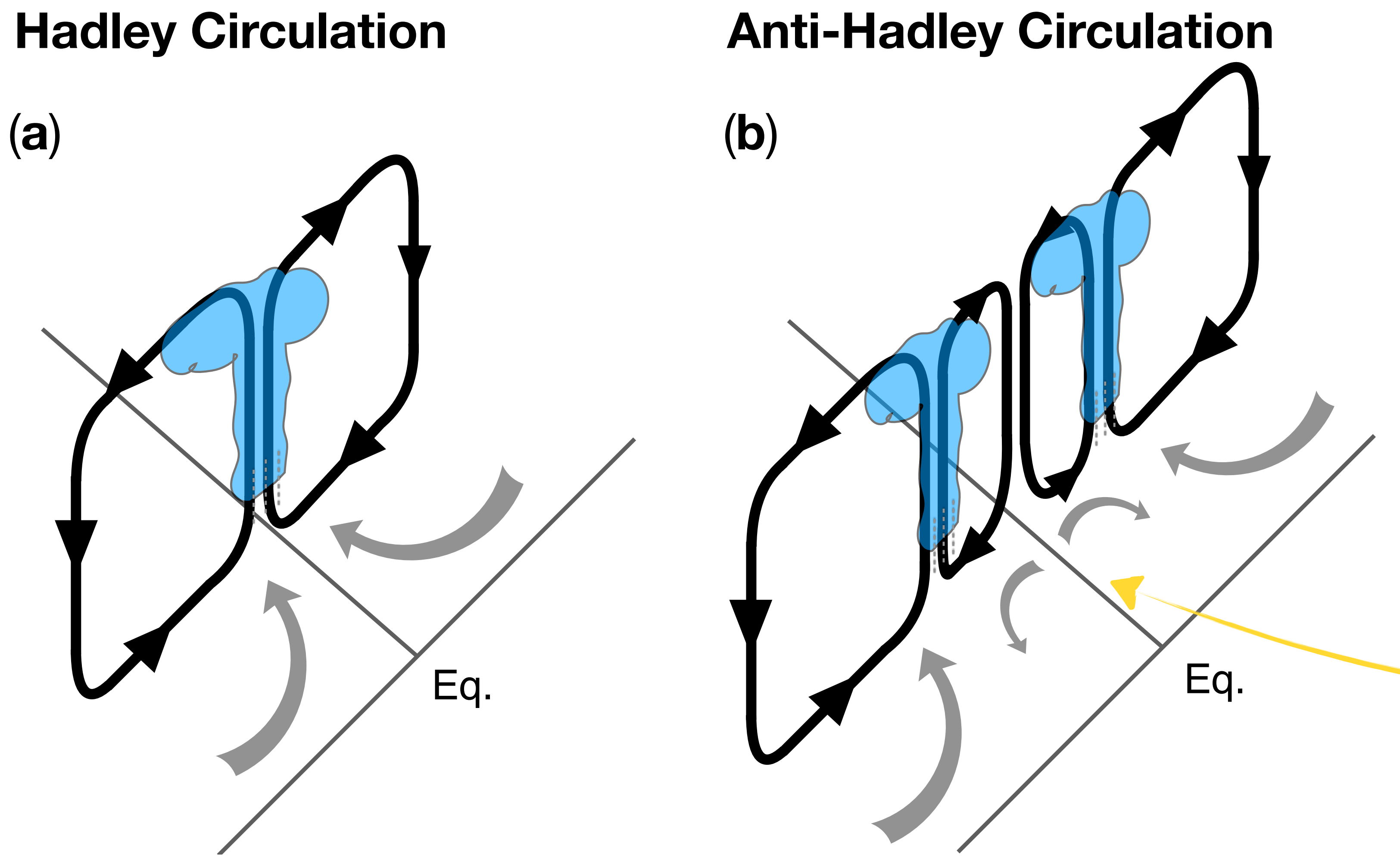


Decomposing F^A into mean and eddy components reveals that:

1. The mean component of F_0^A predicts the position of the ITCZ very well
2. Non-monotonic response of atmospheric transient eddies leads to the non-linear response of the ITCZ to asymmetric heating.

Results - Adam 2020

(Single-ITCZ) (Double-ITCZ)

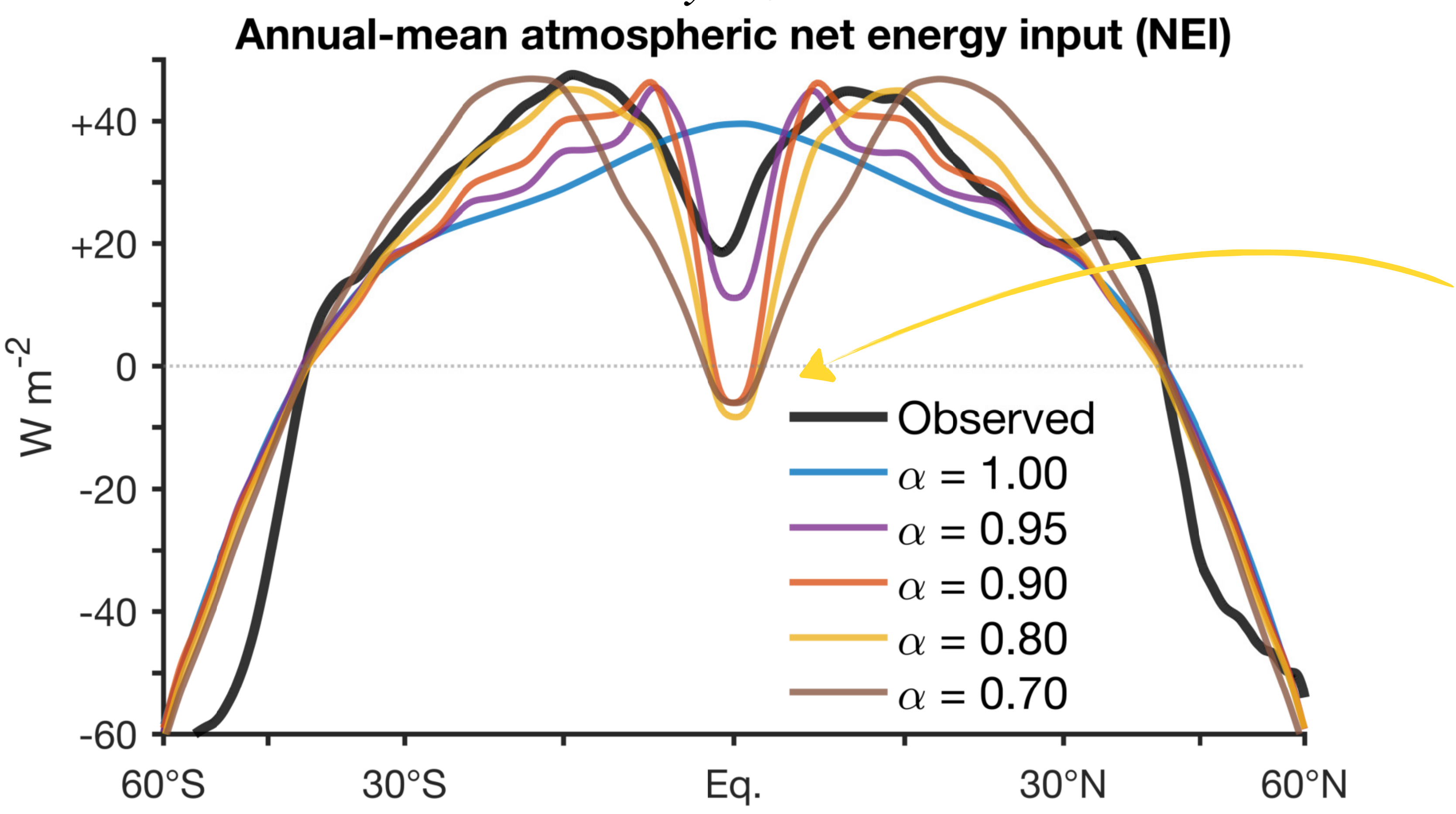


The surface westerlies associated with the anti-Hadley circulation (double-ITCZs) weaken the equatorial easterlies, and therefore equatorial ocean upwelling.

- Equatorial cooling by Ekman upwelling can lead to the emergence of anti-Hadley circulation. The surface westerlies associated with the anti-Hadley circulation limit its extent and intensity.
- More favourable conditions for the emergence of anti-Hadley circulation (and hence double-ITCZs) under hemispherically asymmetric heating, due to stronger equatorial easterlies.

Results - Adam 2020

$\sim \partial_y F_0^A$



Atmospheric net energy input near the equator,

$NEI_0 \sim \partial_y F_0^A$

is set by the balance of:

1. Equatorial cooling
2. Negative anti-Hadley circulation feedback, which prevents NEI from being too negative.

The balance between equatorial cooling and the negative anti-Hadley circulation feedback suggests that over a wide range of climates

$$\partial_y F_0^A \sim NEI_0 \rightarrow 0$$

Results - Adam 2020

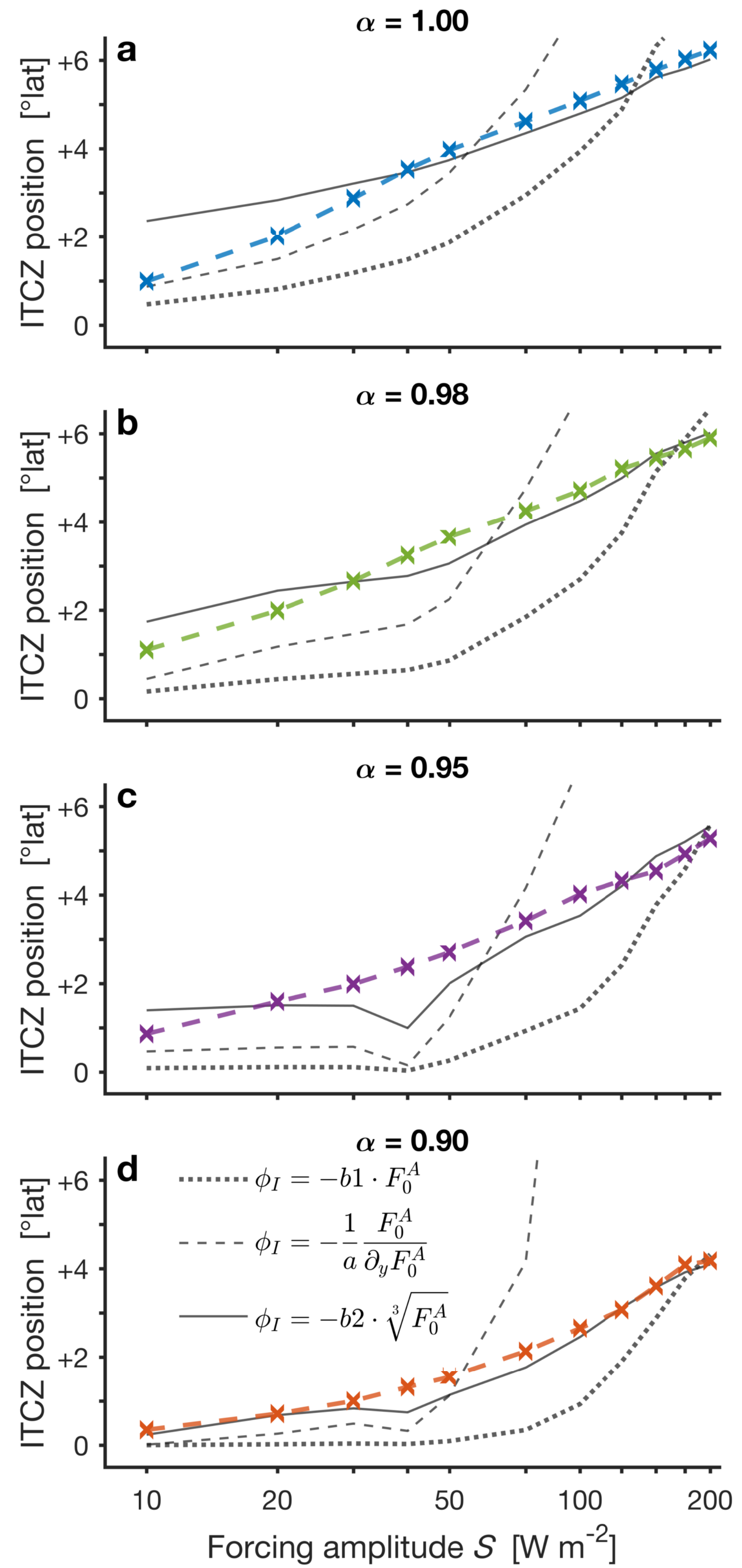
As predicted by energy flux theory, the cubic relation between the position of the ITCZ and cross-equatorial atmospheric energy transport,

$$\phi_{ITCZ} \propto -\sqrt[3]{F_0^A}$$

captures the position of the ITCZ better than the commonly used linear relation,

$$\phi_{ITCZ} \propto -F_0^A,$$

over a wide range of asymmetric heating and ocean stratification values.



Summary

1. Novel parameterization allows explicitly resolving the wind-driven cross-equatorial ocean energy transport.
2. Non-linear response of the ITCZ to hemispherically asymmetric heating, due to non-monotonic response of atmospheric transient eddies
3. Equatorial cooling by Ekman upwelling can lead to the emergence of anti-Hadley circulation. Surface westerlies associated with the anti-Hadley circulation limit its intensification.
4. More favourable conditions for the emergence of double-ITCZs (anti-Hadley circulation) under hemispherically asymmetric heating, due to stronger equatorial easterlies.
5. The balance between equatorial cooling and the negative anti-Hadley circulation feedback suggests that over a wide range of climates, $F_0^A \sim NEI_0 \rightarrow 0$
6. In the idealised mode, the approximation associated with $NEI_0 \sim 0$, $\phi_{ITCZ} \propto \sqrt[3]{F_0^A}$, captures the position of the ITCZ better than the commonly-used linear approximation.