

Reduced tropical rain-band asymmetry through the seasonal cycle

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The northward displacement of the Intertropical Convergence Zone is a defining feature of the tropical climate that global models struggle to reproduce. While often attributed to interhemispheric energy imbalance, other processes may also shape its annual-mean structure. Here we use a hierarchy of models—from a fully coupled model to simplified frameworks—to examine how seasonal insolation variations influence the symmetry of the tropical rain band. Using idealized obliquity experiments alongside observations from 1979 to 2024, we show that amplifying seasonal insolation, while preserving hemispheric symmetry in the annual mean, shifts the rain belt towards a more symmetric state. Enhanced austral-summer heating raises southern tropical sea surface temperatures above a convective threshold, triggering a transient southern rain band amplified by wind–evaporation–surface temperature feedback, while convection remains suppressed outside this season south of the Equator. This seasonally selective response thus affects the annual mean. The rain-belt position thus reflects the nonlinear integration of seasonal dynamics rather than a simple response to annual-mean forcing. Consistently, many models overestimate southeastern tropical Pacific sea surface temperature seasonality, contributing to the double rain-belt bias. Our findings highlight the need for improved representation of seasonal processes in models to better capture annual-mean rainfall patterns.

The Intertropical Convergence Zone (ITCZ) is the dominant rain band of the tropical atmosphere, marking the region of low-level convergence and deep convection near the Equator. In the present climate, the annual- and zonal-mean ITCZ is displaced north of the Equator, a feature known as the interhemispheric ITCZ asymmetry. From an energetic perspective, the annual-mean ITCZ coincides with the latitude where the column-integrated meridional atmospheric energy transport changes sign, whereby its northward displacement reflects an imbalance in the hemispheric energy budgets^{1–5}. This imbalance is traditionally attributed to asymmetric boundary conditions, such as

continental geometry, land–sea contrast and cross-equatorial ocean heat transport (OHT)^{3,6–12}. Within the tropics, the wind–evaporation–SST (WES) feedback acts as a primary process-level mechanism sustaining the cross-equatorial gradients in sea surface temperature (SST) and precipitation, particularly over the eastern Pacific (EP) and Atlantic (ATL), where the asymmetry is most pronounced^{13,14}.

While the energetic framework provides a robust constraint on the annual-mean state, the ITCZ undergoes substantial seasonal migration in response to the solar declination. In March, as Southern Hemisphere (SH) tropical oceans reach their seasonal SST maximum,

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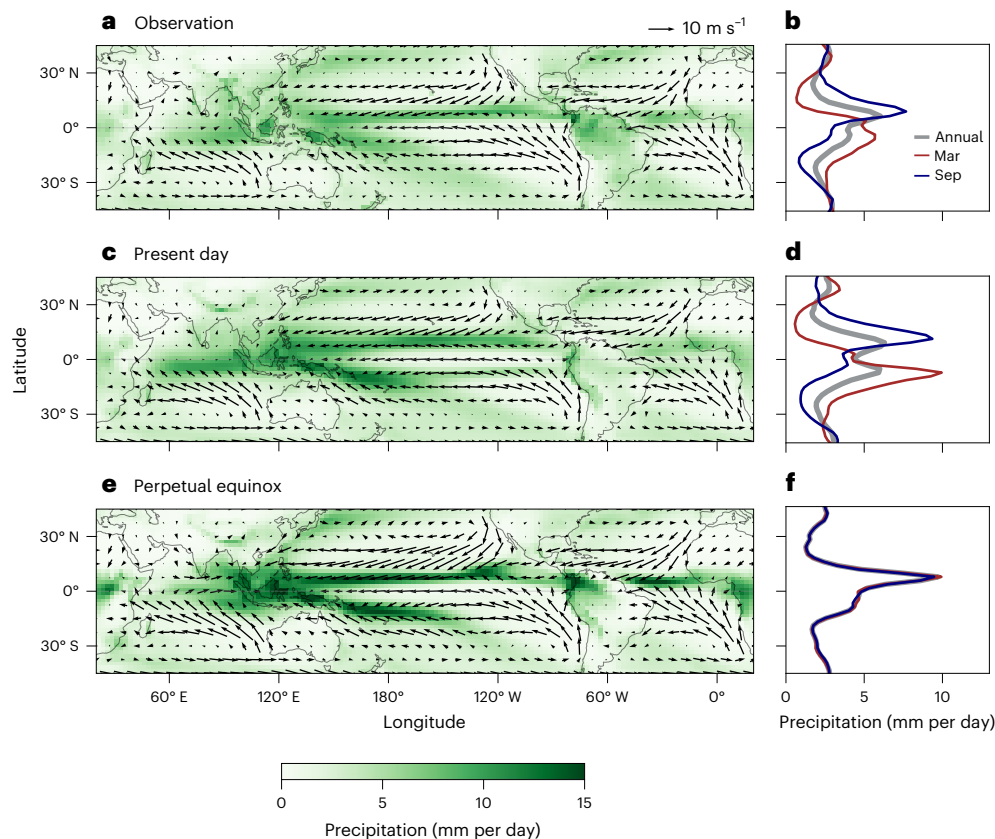


Fig. 1 | The annual-mean ITCZ asymmetry in observation and GCM simulations. **a**, The spatial distribution of observed annual-mean precipitation. **b**, The observed zonal mean annual-mean (grey), March-mean (red) and September-mean (blue) precipitation. **c,d**, The same as in **a** (**c**) and **b** (**d**), respectively, but for model simulation of present-day conditions. **e,f**, The same

as in **a** (**e**) and **b** (**f**), respectively, but for model simulations of perpetual equinox condition. The pattern correlation coefficients between simulated and observed tropical precipitation over EP and ATL (180° – 0° , 20° S– 20° N) are 0.58 and 0.75 for present-day and perpetual equinox conditions, respectively.

a secondary ITCZ branch briefly emerges south of the Equator in the EP, creating a transient double ITCZ structure^{15,16}. In observations, this southern branch remains weaker and shorter-lived compared with its northern counterpart. However, coupled general circulation models (GCMs) systematically overestimate the strength and persistence of this SH branch, leading to the well-known double ITCZ bias in the annual mean^{17–19}. The close association between seasonal evolution errors and climatological biases raises the possibility that the annual-mean state reflects not only annual-mean forcing, but also seasonally varying processes that models fail to capture accurately.

Previous studies have explored how seasonality influences tropical rainfall using highly idealized numerical experiments, such as artificially lengthening the model year or modifying Earth's obliquity. Extending the SH summer allows the southern ITCZ to intensify and dominate during the austral warm season²⁰, while increased obliquity drives a larger seasonal excursion of the ITCZ away from the Equator²¹. These experiments demonstrate that the seasonal cycle exerts strong control on the timing and amplitude of ITCZ migration. However, as changes in seasonal forcing preserve the hemispheric symmetry of annual-mean insolation, it remains unclear how such seasonal modulations translate into a systematic change in the annual-mean ITCZ asymmetry.

In this study, we demonstrate that the strength of the seasonal cycle is a primary control on the annual-mean ITCZ position, operating via a nonlinear seasonal rectification. Using a hierarchy of numerical models, we find that strengthening the seasonal cycle leads to a more symmetric annual-mean ITCZ, even though the hemispheric symmetry in annual-mean solar forcing is preserved. This response

occurs because enhanced austral-summer heating allows SH tropical SSTs to periodically exceed the convective threshold, activating a transient southern ITCZ branch. Once activated, the WES feedback preferentially amplifies SH convection and weakens the northern ITCZ. Because this coupled response is strong in austral summer but weak during the rest of the year, the seasonal asymmetry survives annual averaging as a reduced northward ITCZ displacement. By isolating this threshold-gated seasonal WES feedback, we provide a dynamical explanation for ITCZ asymmetry that complements annual-mean energetic interpretations.

ITCZ asymmetry in full-complexity GCM simulations

To investigate how seasonal cycle intensity influences the annual-mean ITCZ, we use a fully coupled GCM and modulate seasonal forcing by varying the Earth's obliquity. While palaeoclimate records have revealed obliquity-driven changes in ITCZ migration^{22–24}, the lack of observational evidence in the EP and ATL sectors, where ITCZ asymmetry is most pronounced in the present-day climate (Fig. 1a), necessitates a modelling approach. We start by comparing observed annual-mean precipitation with two extreme model cases: present-day (23.5° obliquity) and perpetual equinox (0° obliquity) conditions.

In observations, the ATL and EP sectors feature a concentrated rain band north of the Equator in the annual mean (Fig. 1a). While a secondary rain band (the South Pacific Convergence Zone, SPCZ) exists in the western Pacific and the Indian Ocean ITCZ resides south of the Equator, the zonal-mean precipitation maximum remains distinctly in the Northern Hemisphere (NH; Fig. 1d, grey curve). Our present-day simulation

captures these large-scale patterns but overestimates SH precipitation in the ATL and EP sectors, resulting in the classic ‘double ITCZ bias’ (Fig. 1b,e). This double ITCZ bias vanishes in the perpetual equinox simulation, where the seasonal cycle is muted by design (Fig. 1c,f). The latter simulation also produces a spatial pattern more closely resembling observations (Fig. 1c). We define a double ITCZ index that quantifies the relative strength of SH tropical precipitation (Methods; 0 for absence of SH precipitation and 1 for equal strength of double ITCZ branches), and this index decreases from 0.94 in the present-day simulation to 0.76 under perpetual equinox, compared with 0.84 in observations. Because the two simulations preserve hemispheric symmetry in annual-mean insolation but differ in seasonal solar forcing, this contrast motivates a systematic examination of how seasonality influences ITCZ asymmetry.

To further quantify the relationship between the seasonality and equatorial asymmetry of ITCZ, we conducted a suite of simulations by varying obliquity from 0° to 30° . We use the low-level cross-equatorial southerly wind as a metric of interhemispheric asymmetry, which reflects the differential convergence and exhibits a linear relationship with the double ITCZ index (Supplementary Fig. 1; $r = -0.997$). As the seasonal cycle strengthens with increased obliquity, the annual-mean southerly wind decreases gradually over most longitudes (Fig. 2a), and its zonal average exhibits a robust monotonic decrease (Supplementary Fig. 2): from 1.12 m s^{-1} in the perpetual equinox simulation to 0.50 m s^{-1} in the present-day simulation, compared with 1.05 m s^{-1} in observations. This confirms that a stronger seasonal cycle systematically reduces annual-mean ITCZ asymmetry. This relationship is insensitive to setting eccentricity to zero (Supplementary Fig. 2), so we hereafter focus on obliquity-driven seasonality.

In observations and model simulations (Figs. 1 and 2a), the strongest southerlies are concentrated over the ATL and EP sectors and decay westward toward the SPCZ^{25,26}. We focus our subsequent analysis on these two primary sectors, specifically at 95° W and 23° W , where buoy observations are available to compare. To explore the mechanisms behind the weakening of ITCZ asymmetry by seasonal cycle, we examine the seasonal evolution of the winds within the EP and ATL (Fig. 2b,c). As obliquity and seasonality increase, the reduction in cross-equatorial southerly wind is most pronounced during the SH warm season (February–April, FMA). In the opposite season (August–October, ASO), the southerly wind at the Equator increases by a smaller margin. This contrast is further quantified by presenting the cross-equatorial wind as a function of obliquity (Fig. 2d,e): in both sectors, the decrease in FMA southerly (blue dots) dominates the modest increase in ASO (red dots), shifting the annual-mean state (grey dots). This unequal seasonal response is the first signature of nonlinear rectification: the austral-summer weakening of the northward ITCZ asymmetry is stronger than the opposite-season strengthening, so the seasonal perturbation leaves a residual imprint on the annual mean.

Seasonal rectification via threshold-gated WES feedback

The WES feedback provides a process-level link between SST gradients, cross-equatorial winds and ITCZ asymmetry. A warm SST anomaly on one side of the Equator enhances local convection and drives cross-equatorial flow; under background trade winds, the resulting wind-speed anomalies alter evaporation in a way that reinforces the original SST gradient^{13,14}. This feedback can amplify hemispheric asymmetries and propagate them westwards, consistent with the observed and simulated structure of cross-equatorial winds (Figs. 1 and 2a).

The modulation of annual-mean ITCZ asymmetry by the seasonal cycle arises because the WES feedback is gated by the nonlinear threshold of tropical convection. Physically, the SST threshold arises because boundary-layer moist static energy is closely tied to local SST, whereas tropical free-tropospheric temperature is efficiently homogenized by equatorial waves and strongly constrained by the Indo-Western

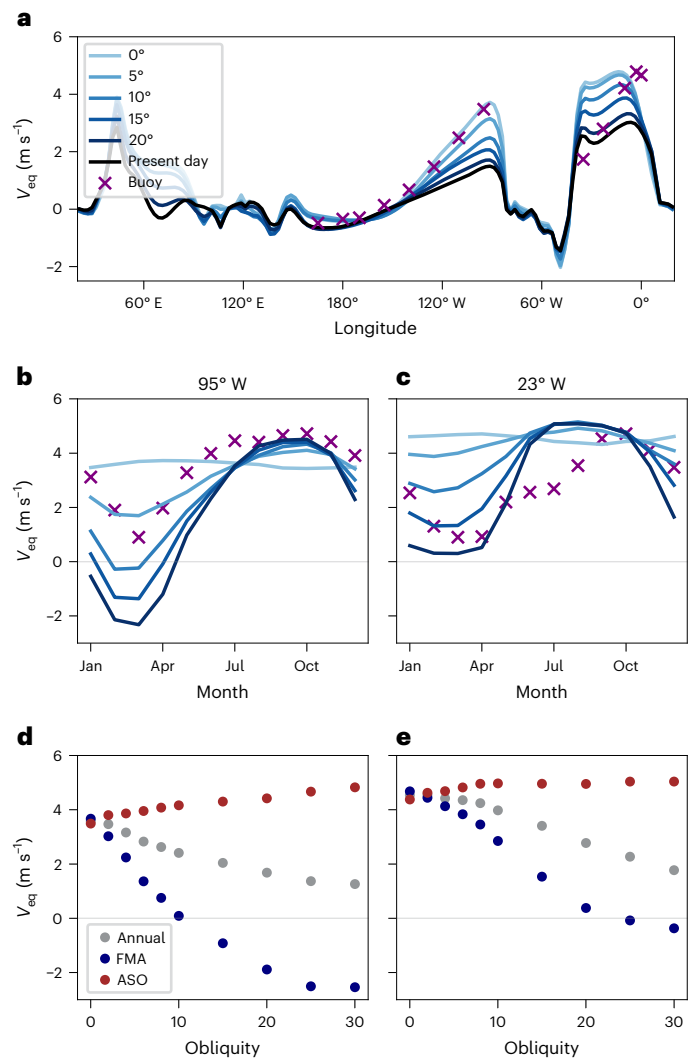


Fig. 2 | The cross-equatorial wind in response to the strength of seasonal cycle. **a**, The annual-mean southerly wind at 10 m elevation as a function of longitude in model simulations of varying obliquity; observed annual-mean southerly winds measured at 4 m elevation from moored buoys are marked by crosses for comparison. **b,c**, The southerly wind at 95° W (representing EP; **b**) and 23° W (representing ATL; **c**). **d,e**, The annual-mean, FMA-mean and ASO-mean cross-equatorial low-level wind averaged over the EP (**d**) and ATL (**e**) as a function of obliquity. The unit for winds is m s^{-1} .

Pacific warm pool^{27–29}. Deep convection over cooler tropical oceans is therefore inhibited unless local SST becomes warm enough to generate deep-layer instability, with this critical value often approximated by the tropical-mean SST^{30–32}. We use this threshold diagnostically, rather than as a strict pointwise boundary for precipitation. When seasonal forcing is weak, SH SST remains below convective threshold year-round, confining precipitation and its seasonal modulation to the NH. In this regime, the annual-mean cross-equatorial wind remains close to the perpetual-equinox state. Once seasonal heating becomes sufficiently strong, however, SH SST exceeds the threshold during the austral warm season, activating a transient southern ITCZ branch that engages the WES feedback^{33–35}. This threshold-gated activation produces a strong austral-summer reduction in cross-equatorial southerly flow. Because the opposite-season response remains weak when SH convection is inactive, the seasonal wind response does not cancel over the year, reducing the annual-mean southerly wind and weakening the northward ITCZ asymmetry. This mechanism is illustrated in the schematic of Supplementary Fig. 3.

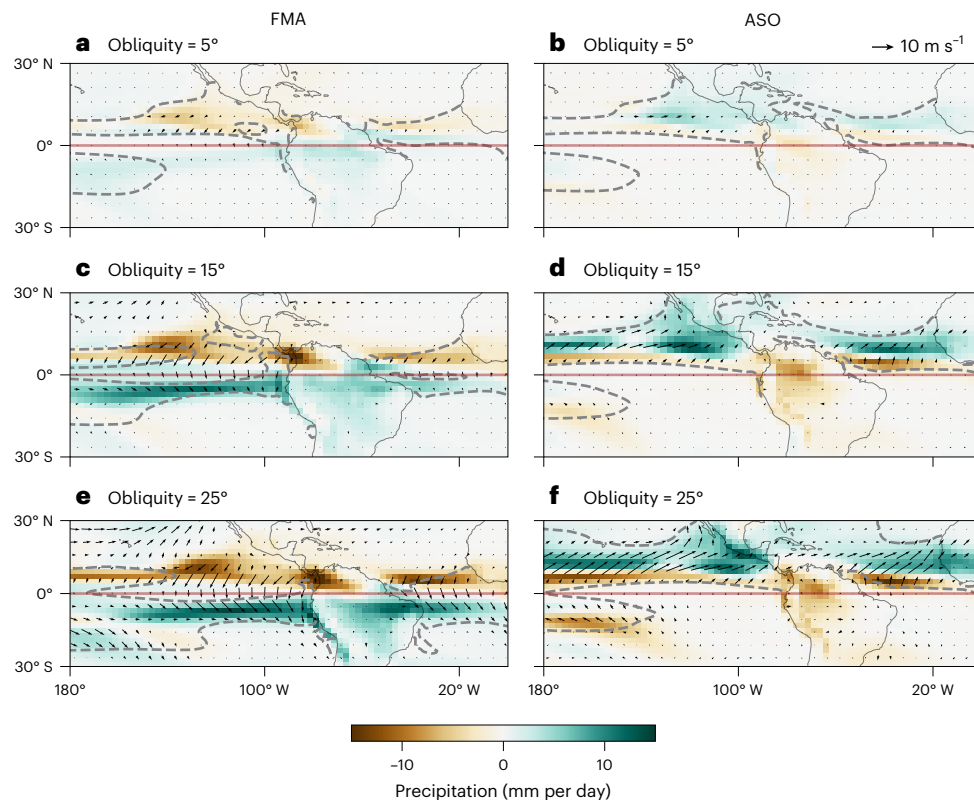


Fig. 3 | Precipitation and low-level wind responses to varied strength of seasonal cycle. **a–f**, The responses are represented by anomalies in non-zero-obliquity simulations compared with perpetual equinox condition, for obliquities of 5° (**a,b**), 15° (**c,d**) and 25° (**e,f**) in FMA (left column) and

ASO (right column). Dashed grey contours mark the convective threshold in non-zero-obliquity simulations (estimated by averaging SST between 20° S and 20° N).

Our GCM analysis supports this mechanism. Compared with the perpetual equinox, increased obliquity provides more solar radiation to the SH from September to March, leading to warmer SSTs and enhanced FMA precipitation south of the Equator (Fig. 3a–c and Supplementary Fig. 4a–c); meanwhile, NH precipitation is reduced, yielding a meridional dipole in precipitation anomalies centred at approximately 10° N/S. Notably, this enhanced SH precipitation does not develop substantially until obliquity reaches 10–15° such that local SST exceeds the convective threshold, marking the threshold-governed activation of SH convection, accompanied by anomalous cross-equatorial northerly winds (Fig. 3b,c).

By contrast, the response during the boreal warm season (ASO) is fundamentally different (Fig. 3d–f and Supplementary Fig. 4d–f). While increased obliquity enhances NH warming, it primarily drives a northward displacement of the existing NH ITCZ rather than an inter-hemispheric shift. Because SH precipitation is already sparse and SSTs remain below the convective threshold, the cooler SH does not produce a comparable compensatory reduction in rainfall. Consequently, the cross-equatorial wind response is largely absent in ASO. Thus, while seasonal solar forcing is interhemispherically symmetric over the year, its impact on ITCZ asymmetry is muted in ASO but amplified in FMA. The GCM simulations therefore reveal a seasonally selective pathway: enhanced seasonal forcing activates SH convection and WES feedback in austral summer, but produces no comparable opposite-season response. This unequal growth rectifies the seasonal cycle into a weaker annual-mean ITCZ asymmetry.

Verifications with reduced-order models

The GCM simulations suggest that seasonal rectification arises from threshold-gated WES feedback, but full-physics models cannot isolate this pathway cleanly. We therefore distil the dynamics into a simplified

two-dimensional (2D) tropical atmosphere–ocean model that couples a tropical mixed-layer ocean with a Matsuno–Gill-type atmosphere^{36,37} (Methods). Despite reduced complexity, the 2D model reproduces the characteristic annual-mean southerly winds over the equatorial Pacific that decay westward across the basin, matching the spatial and temporal features observed in the comprehensive GCM (Fig. 4a; cf. Fig. 2a).

In the 2D model, as the seasonal cycle strengthens, the cross-equatorial wind in the EP region weakens substantially during the austral warm season (Fig. 4b,c; cf. Fig. 2b–e). Crucially, when seasonal forcing is weak, the wind changes in FMA and ASO nearly cancel each other, leaving the annual-mean state unchanged (Fig. 4a,c), a result that mirrors our GCM findings (Fig. 2d,e). It is only when seasonal insolation is strong enough to push SH SSTs above the convective threshold (Supplementary Fig. 5) that the southerly wind declines sharply and even reverses, producing a net reduction in the annual mean (Fig. 4c). These results show that seasonal rectification does not require the full complexity of the GCM; it emerges once convective thresholding and WES feedback act together.

We further condense these dynamics into a three-variable conceptual model containing only NH SST, SH SST and cross-equatorial meridional wind (Methods). The prognostic equations retain three essential ingredients: WES feedback, a prescribed convective threshold, and an annual harmonic of solar forcing. Local SST anomalies affect convective heating only where SST exceeds the threshold, while the resulting cross-equatorial wind feeds back on SST through wind-induced evaporation. Despite its simplicity, this three-variable system demonstrates remarkable fidelity, with its temporal evolution and sensitivity to seasonal intensity aligning closely with both the 2D model and observations (Fig. 4d,e; cf. Figs. 4b,c and 2b–e). The model confirms that annual-mean asymmetry is modulated by a seasonal

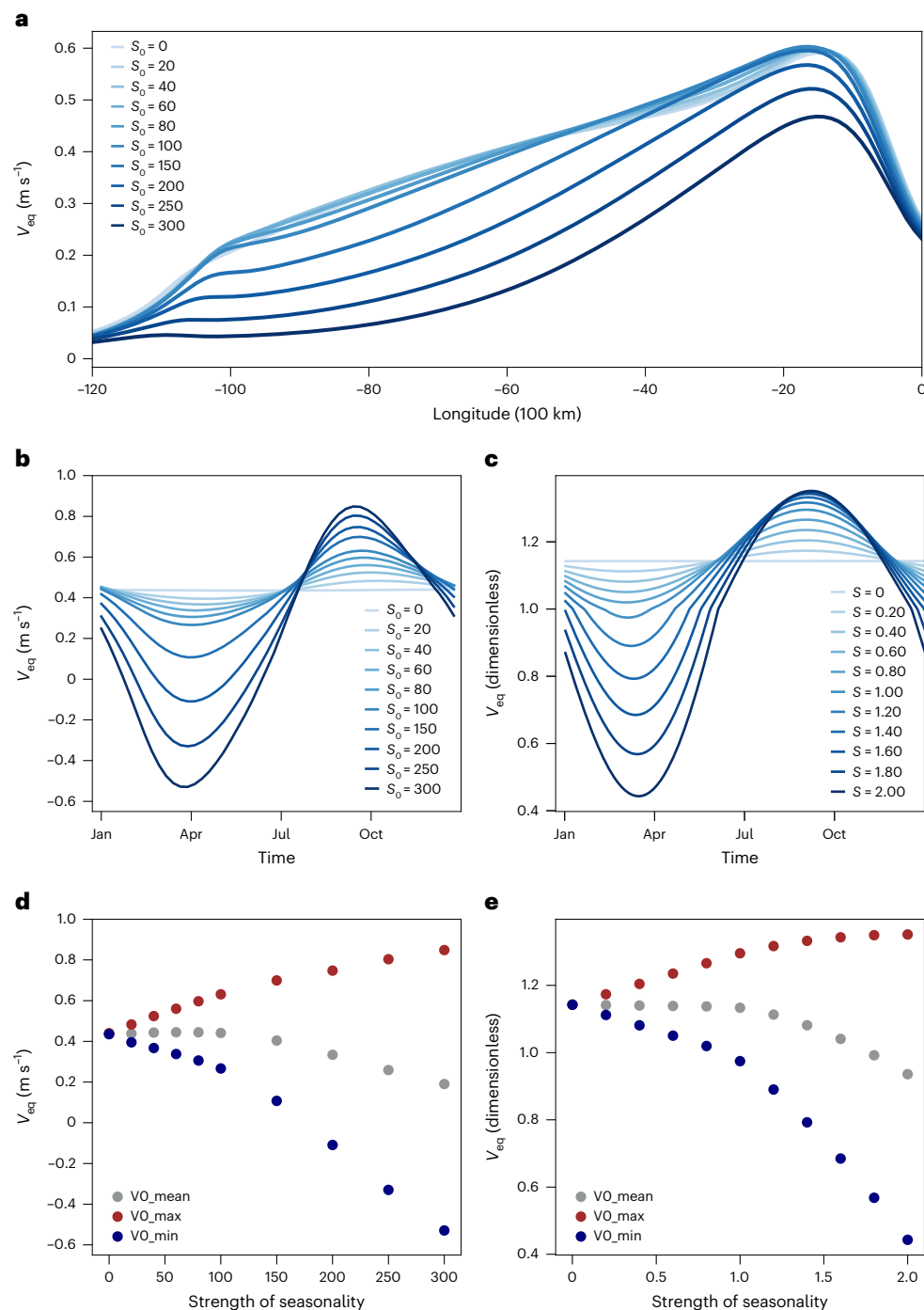


Fig. 4 | The ITCZ asymmetry in the reduced-order models. a, The annual-mean cross-equatorial wind simulated by the 2D model with different strengths of seasonal solar forcing. The x axis denotes the distances from the eastern ocean boundary, mimicking the coast of the Americas. **b**, The seasonal evolution of cross-equatorial wind at $x = -5,000$ km simulated by the 2D model with different

strengths of seasonal solar forcing. **c**, The same as in **b**, but for the wind simulated by three-variable model. **d, e**, The annual mean, maximum and minimum cross-equatorial winds in **b** (**d**) and **c** (**e**), respectively, as a function of strength of seasonality.

‘convective switch’: when SH SST exceeds the threshold in FMA, WES feedback strengthens the cross-equatorial response and the climatological southerly wind briefly collapses. During the rest of the year, the wind response to an enhanced seasonal cycle is weaker because convective anomalies remain largely confined to the NH.

Taking the annual average of the wind equation in this three-variable model yields a heuristic rectification index for the component of the seasonal wind response that survives integration over the year (Methods). Under simplifying assumptions, this index scales with

the exceedance of the seasonal maximum SH SST above the convective threshold. The index correlates well with cross-equatorial winds in the GCM simulations (Supplementary Fig. 6), underscoring the central role of nonlinear rectification in linking the seasonal cycle to ITCZ asymmetry.

Model biases and broader implications

The mechanistic link between the seasonal cycle and annual-mean asymmetry offers a perspective on the pervasive double-ITCZ bias in

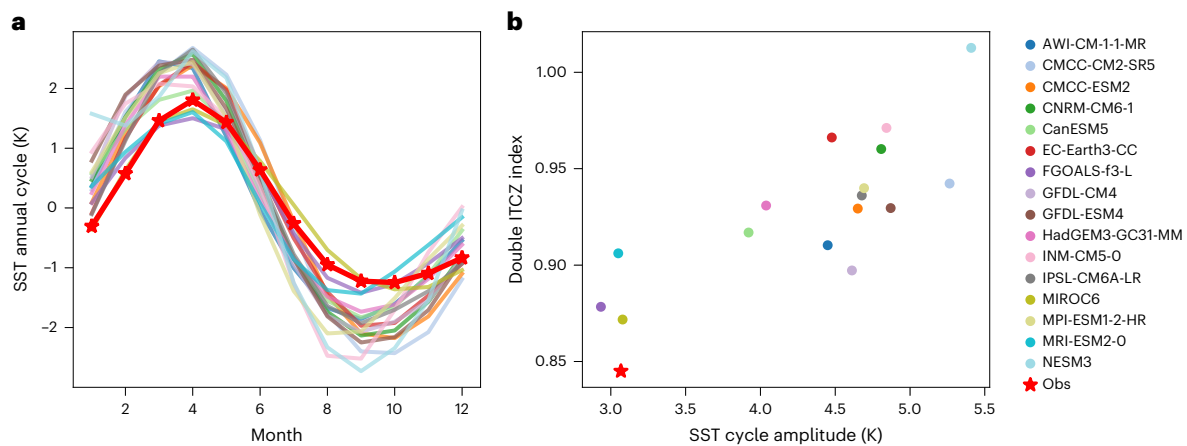


Fig. 5 | Intermodel relationship between SST annual cycle and double ITCZ bias in CMIP6 historical simulations. a, The climatological SST annual cycle with the annual-mean subtracted. **b,** The relationship between amplitude of SST annual cycle and double ITCZ index. The amplitude of climatological SST cycle

is calculated as the hottest month minus the coldest month. The coloured round dots and curves are from individual CMIP6 models, and the red star and curve are from the observation (Obs). The SST is averaged over 100–130° W, 3–8° S. The correlation for the CMIP6 models in **b** is $r = 0.77$, $P < 0.001$.

comprehensive climate models. The GCM employed here substantially overestimates the amplitude of the seasonal SST cycle in the tropical southeastern Pacific (100–130° W, 3–8° S), a bias so pronounced that the simulated seasonality aligns with observations only when obliquity is artificially reduced to about 10° (Supplementary Fig. 7).

Our analysis of the Coupled Model Intercomparison Project Phase 6 (CMIP6) multimodel ensemble (Methods) confirms this is a systemic issue: most models exhibit an exaggerated seasonal SST cycle in the same tropical Pacific region, despite being driven by realistic solar forcing (Fig. 5a). The amplitude of climatological SST cycle in the multimodel mean is 1.3 K (42%) higher than that in observations. This excessive seasonality allows SH SSTs to exceed the convective threshold too frequently and persistently³⁸, prematurely activating the southern ITCZ branch and rectifying the seasonal SST bias into an annual-mean double-ITCZ bias across models (Fig. 5b; the multimodel average of the double ITCZ index is 0.94, as opposed to 0.84 in observations). Models with more realistic seasonal SST amplitudes consistently achieve a more accurate annual-mean state, revealing a robust intermodel correlation between seasonal SST biases and ITCZ asymmetry errors (Fig. 5b).

Atmospheric GCMs forced by observed SST outperform their coupled counterparts in capturing ITCZ asymmetry, a result linked to SST errors in coupled simulations^{2,39–41}. Our analysis further suggests that the double-ITCZ bias is not merely a mean-state error but includes a nonlinear rectification of seasonal SST biases (Supplementary Fig. 6b), pointing to seasonal mixed-layer dynamics, cloud-radiative feedbacks, and their nonlinear interaction with the convective threshold as key targets for model improvement^{2,39–43}.

Beyond model biases, the rectification mechanism also extends beyond the traditional energetic interpretation of ITCZ position. The ITCZ is often understood as adjusting to cross-equatorial OHT for energetic compensation. However, our diagnostics show that, with increasing obliquity, reductions in interhemispheric energy imbalance arise primarily from changes in top-of-atmosphere radiative fluxes rather than surface fluxes. Moreover, global cross-equatorial OHT increases with obliquity, which alone would imply a more northward-displaced ITCZ (Supplementary Fig. 8), yet the ITCZ instead shifts towards greater symmetry. This demonstrates that seasonal rectification can override the tendency implied by OHT alone, not by negating energetic constraints, but by reshaping the annual-mean energy budget through nonlinear seasonal processes.

This framework carries broader implications across timescales. During periods of elevated obliquity in Earth's history, enhanced

seasonal forcing may have promoted a more symmetric tropical precipitation structure than inferred from annual-mean energetics alone. Looking forward, non-uniform SST warming may alter the convective threshold and the geographic extent of active convection, and future changes in the seasonal duration of SH convection could modify annual-mean ITCZ asymmetry through the same rectification pathway identified here.

More generally, annual-mean tropical climate patterns cannot be interpreted solely as equilibrium responses to annual-mean forcing. In the ITCZ problem, a short seasonal window of threshold-crossing SH convection leaves a lasting imprint on the annual-mean climatology. Recognizing this rectification pathway provides a dynamical bridge between seasonal variability and climatological structure, and underscores that improving the representation of seasonal tropical SST evolution is essential for correcting persistent annual-mean ITCZ biases.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41561-026-02046-6>.

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Methods

Double ITCZ index

We define a double ITCZ index (dITCZ) to quantify the extent of inter-hemispheric ITCZ asymmetry,

$$\text{dITCZ} = 1 - \frac{P_N - P_S}{P_N + P_S} = \frac{P_S}{(P_N + P_S)/2} \quad (1)$$

where P_N and P_S represent the annual-mean precipitation averaged over 5–15° N and 5–15° S, respectively. Mathematically, this index reflects the strength of the southern ITCZ branch scaled by the average strength of northern and southern branches. dITCZ being zero denotes absence of precipitation in the southern ITCZ branch, whereas 1 denotes equal strength between northern and southern ITCZ branches.

Observation and reanalysis datasets

Precipitation data from 1979 to 2024 are obtained from the Global Precipitation Climatology Project (GPCP) Monthly Analysis Product⁴⁴. The monthly SST is from version 5 of the Extended Reconstructed Sea Surface Temperature (ERSST) dataset⁴⁵. Surface wind fields at 10 m height, also from 1979 to 2024, are taken from the European Centre for Medium-Range Weather Forecasts Reanalysis v5⁴⁶. In addition, buoy wind measurements at nominal 4 m height from the Tropical Atmosphere Ocean (TAO) and the Prediction and Research Moored Array in the Atlantic (PIRATA) moored buoy arrays^{47,48} are used to validate the reanalysis data and compare with GCM simulations.

Coupled GCM simulations

We use the Geophysical Fluid Dynamics Laboratory's coupled model version 2.1 (CM2.1)⁴⁹ to conduct fully coupled simulations. CM2.1 provides a realistic representation of tropical climate dynamics, including mean states and variability patterns^{50,51}. To sample the different amplitudes of seasonal solar cycle, we vary the obliquity from 0° to 30° while keeping other orbital parameters fixed. For each value of obliquity, the simulation is branched from a historical control run in 1990 and integrated for 1,000 years under fixed 1990-level radiative forcing. The final 200 years of each simulation are used for analysis.

The Earth's orbital eccentricity has also been argued to contribute to the seasonal evolution of tropical SSTs, sometimes referred to as 'distance effect'^{52,53}. To quantify the relative importance of orbital eccentricity in the obliquity-driven modulation, we perform parallel simulations with the orbital eccentricity additionally set to 0 for obliquity being 10°, 15°, 20°, 25° and 30°.

Simplified 2D tropical atmosphere–ocean model

We adopt a minimal coupled model, consisting of a shallow-water atmosphere and a slab mixed-layer ocean, to investigate the key mechanisms driving the ITCZ response to seasonal solar forcing²⁵. The model framework is summarized below.

A shallow water equations model^{36,37} is adapted for the atmosphere:

$$\varepsilon u - yv = -\frac{\partial \Phi}{\partial x} \quad (2)$$

$$\varepsilon v + yu = -\frac{\partial \Phi}{\partial y} \quad (3)$$

$$\varepsilon \Phi + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -Q \quad (4)$$

where u and v are anomalous zonal and meridional velocities, Φ is anomalous geopotential and ε is the damping rate. The latent heating to the atmosphere is given by

$$Q = \frac{K_Q}{(\beta C^S)^{\frac{1}{2}}} (T - T_c) \mathcal{H}(T - T_c) \quad (5)$$

where $\mathcal{H}(\cdot)$ is the Heaviside function, T_c is the convection threshold, K_Q is the thermal coupling coefficient, C is the long gravity wave speed and β is the meridional gradient of Coriolis parameter at the Equator. Note that x and y are non-dimensionalized by the deformation radius $L_D = \sqrt{C/\beta} = 1,400$ km, velocities u and v by C , and geopotential Φ by C^2 . The non-dimensional damping rate $\varepsilon = 0.18$, corresponding to an e -folding timescale of approximately 2 days. See Supplementary Table 1 for a complete list of parameters and their values.

The temperature of the mixed layer ocean is determined by the equation

$$\frac{\partial T}{\partial t} = \frac{Q_0 - Q_w - C_E^* |U| q_s(T)}{\rho c_p h} \quad (6)$$

where $C_E^* = C_E L \rho_a (1 - \text{RH})$ is the effective drag coefficient, L is the latent heat and RH is the relative humidity. The wind speed felt by the ocean surface is not allowed to fall below a minimum value $U_{\min}$ due to unresolved high frequency atmospheric disturbances, that is, $|U| = \max(U_{\min}, \sqrt{(u_0 + Cu)^2 + (Cv)^2})$, where u_0 is a constant background trade wind and Cu and Cv are the dimensional winds. The saturated moisture content $q_s(T)$ is given by the Clausius–Clapeyron equation

$$q_s(T) = q_0 \exp \left[\frac{L}{R_*} \left(\frac{1}{T_0} - \frac{1}{T} \right) \right] \quad (7)$$

The seasonal radiative flux is parameterized as

$$Q_0(t) = C_E^* U_{\min} q_s(T^*) + S_0 \sin \theta \sin \left[2\pi \left(t - \frac{79}{365} \right) \right] \quad (8)$$

where $T^* = T_e + \Delta T(y/L_y)^2$ is the annual-mean equilibrium temperature, with T_e denoting the equilibrium temperature at the Equator and ΔT the equilibrium temperature gradient, S_0 is a parameter controlling the amplitude of seasonal solar forcing, varying from 0 to 500 W m^{−2}, and θ is latitude. The equatorial upwelling is parameterized as

$$Q_w = 10^{-2} \exp(-2y^2) C_E^* U_{\min} \quad (9)$$

Other parameters are listed in Supplementary Table 1 as well.

The atmosphere is simulated on a domain defined by $-10L_D \leq x \leq 10L_D$ and $-3L_D \leq y \leq 3L_D$, with a cyclic boundary condition in x and Dirichlet conditions $u = v = \Phi = 0$ at $y = \pm 3L_D$. The active single ocean basin spans $-10L_D \leq x \leq 0$ and $-L_D \leq y \leq L_D$. Outside the ocean basin, a weak dipolar heating perturbation $\hat{Q}$ is introduced where $x > 0$ to break the interhemispheric symmetry; otherwise, the land is inactive and does not interact with the atmosphere. The heating perturbation $\hat{Q}$ satisfies

$$\frac{\sqrt{\beta C^S}}{K_Q} \hat{Q} = \hat{T} \left[e^{-\frac{1}{2} \left(\frac{y-y_0}{y_L} \right)^2} - e^{-\frac{1}{2} \left(\frac{y+y_0}{y_L} \right)^2} \right] \quad (10)$$

where $y_0 = 700$ km, $y_L = 200$ km and $\hat{T} = 0.02$.

Three-variable WES model

To further isolate the core dynamics of the WES mechanism, we construct a minimal reduced-order model that distills the coupled tropical atmosphere–ocean system into three grid points: $T_{N/S}$ represent the SST anomalies north and south of the Equator, and v_0 represents the meridional wind at the Equator. The model equations are

$$\frac{\partial T_N}{\partial t} = av_0(t) - bT_N(t) + s_0 \sin \left[2\pi \left(t - \frac{79}{365} \right) \right] \quad (11)$$

$$\frac{\partial T_S}{\partial t} = -av_0(t) - bT_S(t) + s_0 \sin\left[2\pi\left(t - \frac{79}{365}\right) + \pi\right] \quad (12)$$

$$v_0 = (T_N - T_c)\mathcal{H}(T_N - T_c) - (T_S - T_c)\mathcal{H}(T_S - T_c) \quad (13)$$

Similarly, $\mathcal{H}(\cdot)$ is the Heaviside function and T_c is the convection threshold. a and b are the WES and Newtonian (evaporative) cooling coefficients, and s_0 is a parameter for the strength of the seasonal insolation cycle. All variables are non-dimensional, and we set $a = 2.25$, $b = 4$, $T_c = -0.5$, and s_0 ranging from 0 to 2; following ref. 34, these parameters correspond to damping timescale of around half-day and 3 months for atmosphere and ocean. The initial value at $t = 0$ is $T_{N/S} = \pm 0.001$. It takes less than 5 model years to reach equilibrium, and we present the climatology of 10–15 years in the analysis.

Rectification index

Based on the three-variable model, we introduce a metric for nonlinear rectification in the annual mean cross-equatorial wind. Starting from equation (13), we assume T_N is always above the convective threshold T_c and define the rectification index for reduced asymmetry due to the transient southern ITCZ

$$\text{rect.} = \frac{1}{2\pi} \int_0^{2\pi} (T_S - T_c) \mathcal{H}(T_S - T_c) dt \quad (14)$$

We also assume that T_S evolves as a sine wave, $T_S = A_S \sin(t + \varphi) + \overline{T_S}$, with its annual average $\overline{T_S} < T_c$ and its maximum $\overline{T_S} + A_S > T_c$, where A_S is the amplitude of sine wave. We then obtain

$$\text{rect.} = \frac{A_S}{\pi} \left[\sqrt{1 - q^2} - q \arccos q \right] \quad (15)$$

where $q = (T_c - \overline{T_S})/A_S$. As q increases from 0 to 1, the function within the square bracket varies monotonically from 1 to 0. To simplify the index, we keep only the linear dependency by fitting the function with $1 - q$, and also ignore the factor of $1/\pi$, then

$$\text{rect.} \approx A_S \left(1 - \frac{T_c - \overline{T_S}}{A_S} \right) = \overline{T_S} + A_S - T_c \quad (16)$$

This rectification index simply measures how much the maximum T_S exceeds the convective threshold T_c . For the GCM simulations, T_c can be estimated as the annual-mean SST averaged over the tropics (for example, 20° S–20° N). Considering the simplicity of the three-variable model, this index should be used as a qualitative but not quantitative metric. Nevertheless, this index correlates very well with the simulated cross-equatorial wind in GCMs.

CMIP6 models

We analyse the historical simulations from multiple models participating in CMIP6⁵⁴. Sixteen models that output 10 m wind, which is comparable with ERA5, are considered in this study (see Fig. 5 for a complete list), and 10 m meridional wind, precipitation and surface temperature from 1979 to 2014 in the first realization (r1i1p1f1) of historical simulations are used for analysis.

Statistical test

Linear relationships are quantified using the Pearson product-moment correlation coefficient r , with the two-sided P value derived from a Student's t -test with $n - 2$ degrees of freedom.

Data availability

The GPCP dataset is available at <https://psl.noaa.gov/data/gridded/data.gpcp.html>. The ERSST dataset is available at <https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html>. The ERA5 reanalysis is available

via the Copernicus Climate Data Store at <https://doi.org/10.24381/cds.6860a573>. The buoy observations are available at <https://www.pmel.noaa.gov/gtmba/>. The CMIP6 model simulations are available at <https://esgf-node.ornl.gov/>. The CM2.1 simulations used for the analysis are available via Zenodo at <https://doi.org/10.5281/zenodo.20551035> (ref. 55).

Code availability

The code is available via Zenodo at <https://doi.org/10.5281/zenodo.20551035> (ref. 55).

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Author contributions

P.Z. and S.-P.X. conceived of and designed the study. P.Z. performed the numerical experiments. P.Z. and S.-P.X. conducted the analysis. P.Z. drafted the paper. P.Z., S.-P.X., N.J.L., Y.M.O., D.Y. and T.A.S. contributed to interpreting the results and improving the paper.

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Competing interests

The authors declare no competing interests.

Additional information

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