Response Letter

Dear Reviewer,

We sincerely thank you for your thoughtful, constructive, and insightful comments. Your suggestions have been invaluable in improving the clarity, scientific rigor, and mechanistic interpretation of our manuscript. In response, we have substantially revised the manuscript, incorporated additional analyses to strengthen the proposed mechanism, and provided responses to your comments below. Figures are denoted as Fig. x, Fig. Sx, and Fig. Rx for the main text, Supplementary Information, and this response letter, respectively.

With best regards,
Yufei Liu, on behalf of all coauthors

Point-by-Point Replies to Reviewer #1

Precession affects ENSO variability, which tends to be strong during periods of austral summer perihelion; however, the underlying mechanisms remain contentious. The authors propose that asymmetric continental heating between Afro–Eurasia and Australia at perihelion and aphelion drives the migration of the ITCZ, alters the Pacific east-west thermal contrast, and modulates the threshold for triggering ENSO events. For instance, summer perihelion induces strong warming over Australia (east of the Indo-Pacific ITCZ), shifting the ITCZ and the warm pool eastward, thereby facilitating the development of strong El Niño events. This mechanism bears resemblance to that of extreme El Niño under greenhouse warming, characterized by a reduced west-minus-east equatorial SST gradient.

Nevertheless, the proposed mechanism must be evaluated alongside other suggested processes. While these factors are not necessarily independent, they may be mutually inclusive, at least in part. Furthermore, the current results should be interpreted within the context of ongoing greenhouse warming, particularly regarding its impact on upper-ocean stratification (Cai et al., 2018, Nature). According to this study, we should be experiencing a high ENSO activity period, which aligns with observations. An attribution study (Cai et al., 2021, Nature Reviews Earth & Environment) indicates that ENSO amplitude has increased by over 30% since the 1960s, yet greenhouse warming accounts for only about 10% of this trend. This suggests that other processes likely play a significant role. The 10% increase is primarily attributed to enhanced upper-ocean stratification, despite the authors noting a La Niña-like mean state change. Under greenhouse warming, although rapid warming occurs over the Afro-Eurasian landmass, the effect of oceanic stratification appears to dominate.

Given these competing factors, I recommend that the authors investigate whether differences in upper-ocean stratification between periods of strong Australian warming and periods of strong Afro-Eurasian warming play a contributory role.

REPLY: We sincerely thank the reviewer for this insightful and constructive suggestion. Following your suggestion, we have conducted additional analyses to further evaluate the role of upper-ocean stratification in modulating ENSO variability. These analyses are organized into four steps. First, we diagnose upper-ocean stratification differences between the two end-member experiments (270° and 90° precession phases; **Fig. R1; also included in Fig. S7**). Second, we examine the relationship between upper-ocean stratification and ENSO amplitude across all 24 precession experiments **(Fig. R2)**. Third, we further evaluate the thermocline feedback (α), which represents an important oceanic coupling process through which changes in upper-ocean stratification can influence ENSO growth **(Fig. R3)**. Finally, these diagnostics have been incorporated into the revised Fig. 4, together with other mean-state and Bjerknes feedback indicators, to provide a more comprehensive assessment of the processes linking precessional forcing to ENSO variability. Taken together, these additional analyses suggest that upper-ocean stratification represents an important intermediate oceanic pathway within the proposed framework. Specifically, asymmetric continental heating reorganizes the tropical Indo-Pacific mean state, which subsequently strengthens upper-ocean stratification and thermocline feedback. Together with changes in wind feedback, these oceanic adjustments enhance Bjerknes feedback efficiency and contribute to stronger ENSO variability under the present-day-like precessional configuration.

Lines 14–39 (Abstract): *"Geological records and climate modeling evidence indicate that the El Niño–Southern Oscillation (ENSO) is strongly modulated by Earth's axial precession, yet the mechanisms remain unclear due to interactions among multiple forcings. Using high-resolution climate simulations, we reconstruct ENSO variations across a full precessional cycle. Our results reveal that ENSO is more active when perihelion coincides with austral summer and aphelion with boreal summer, consistent with the orbital configuration of the present-day climate. Through diagnostics of background mean climate evolution and ENSO-related feedback processes, we propose that precession-scale modulations in ENSO variability are governed by east–west asymmetric continental warming. When perihelion occurs during austral summer and aphelion during boreal summer, pronounced warming emerges over Australia (east of the Indo-Pacific Intertropical Convergence Zone (ITCZ)), whereas relative cooling prevails over the Afro–Eurasian continents (west of the Indo-Pacific ITCZ). This east–west thermal contrast drives an eastward shift of the ITCZ and its coupled Walker circulation, accompanied by weakened trade winds, a shallower ocean mixed layer, and enhanced upper-ocean stratification. These changes reduce the thermal inertia of the warm pool, allowing even moderate climate noise to trigger the Bjerknes feedback (including wind and thermocline feedbacks), ultimately magnifying ENSO variability under precessional phases analogous to the modern configuration. Conversely, when perihelion falls in boreal summer and aphelion in austral summer, cooling over Australia and warming over Afro–Eurasian continents force westward displacements of the ITCZ and Walker circulation, strengthen trade winds, force a deeper mixed layer and reduced upper-ocean stratification, suppressing the Bjerknes feedback, thereby dampening ENSO activity during precessional phases corresponding to the Early Holocene. Proxy records from the Indo-Pacific region support these shifts in climatic regimes. This mechanism of zonal asymmetric continental warming establishes a physical link between astronomical precessional forcing and ENSO behavior, and may provide insights to improve assessments of long-term tropical climate variability."*

1. Contrasts in upper-ocean stratification between 90° and 270° precessional phases

Previous studies have shown that enhanced upper-ocean stratification under future greenhouse warming conditions is a key factor contributing to intensified ENSO extremes (Cai et al., 2018, 2021). Although greenhouse gas forcing and precessional forcing arise from fundamentally different external drivers, they regulate ENSO variability through a similar pathway by modifying the background climate state and thereby altering the efficiency of air–sea coupling. Following the reviewer's suggestion, we first focus on the two precession phases corresponding to the weakest and strongest ENSO variability, respectively, and investigate their seasonal variations in upper-ocean stratification.

Following the stratification calculation method adopted by Cai et al., we define the stratification index as the difference between the mean temperature of the upper 100 m and the temperature at 120 m depth within the western–central equatorial Pacific (5°S–5°N, 140°E–150°W) **(Fig. R1; Fig. S7).**

During boreal summer (JJA), the 270° precession phase corresponds to aphelion, and the associated cooling of the African–Eurasian continent weakens the land–sea thermal contrast on the western side of the Indo-Pacific warm pool. This reduced thermal forcing drives an eastward displacement of the Indo-Pacific Warm Pool (IPWP) and tropical convection. As a result, warm-water accumulation in the western–central Pacific is reduced, accompanied by a shallower mixed layer. In contrast, during the 90° phase, perihelion occurs in boreal summer, and enhanced heating over Africa–Eurasia strengthens the continental thermal forcing. This drives a westward migration of the IPWP toward the continent, increasing warm-water convergence and deepening the mixed layer over the western–central Pacific. Consequently, compared with the 90° phase, the 270° phase exhibits a shallower mixed layer, a larger vertical temperature gradient in the upper ocean, and stronger upper-ocean stratification.

A similar but more pronounced stratification contrast occurs during austral summer (DJF), when the dominant continental thermal forcing shifts to Australia, which is located east of the Indo-Pacific warm pool. At the 270° phase, perihelion-induced enhanced heating over Australia drives an eastward migration of the IPWP and convection, accompanied by a shoaling of the equatorial thermocline. Conversely, the 90° phase corresponds to austral summer aphelion, resulting in weaker Australian heating, a westward displacement of the IPWP, and a deeper thermocline structure.

Taken together, the seasonally reversed asymmetric continental heating induced by precession consistently reorganizes the tropical Indo-Pacific mean state throughout the annual cycle. Previous studies have demonstrated that enhanced ocean stratification increases the sensitivity of thermocline variability to wind stress forcing, thereby strengthening the efficiency of the thermocline feedback (α feedback) and amplifying the Bjerknes positive feedback loop. Therefore, the stronger upper-ocean stratification under the 270° precession configuration provides a more favorable background state for efficient air–sea coupling, ultimately contributing to the enhanced ENSO variability observed during this phase.

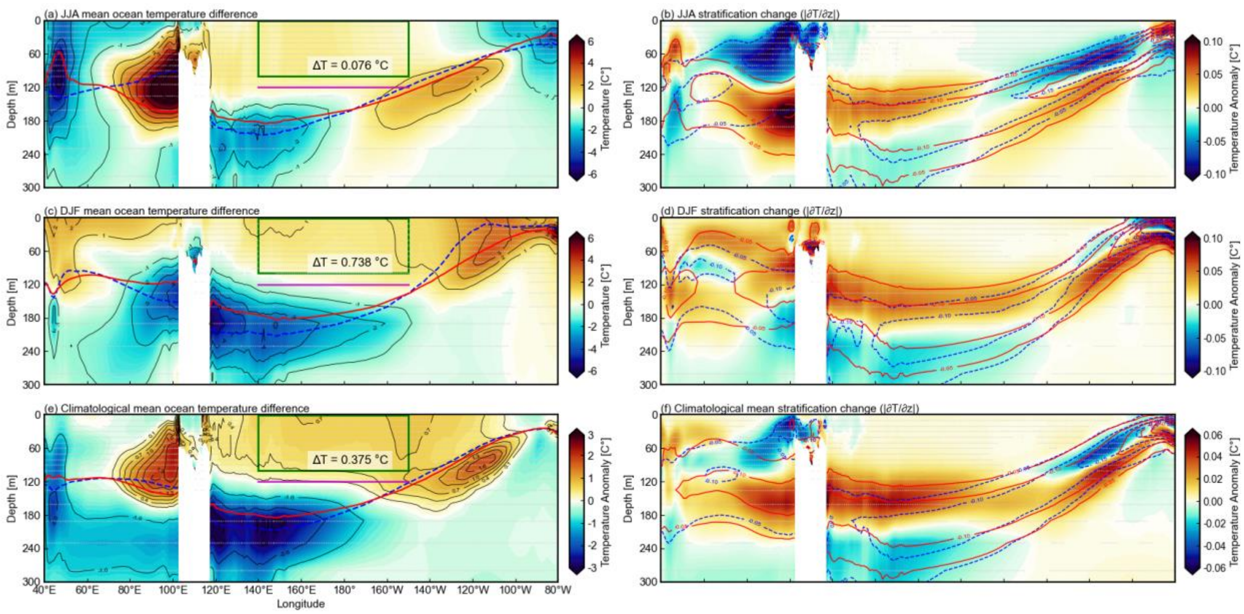

Figure R1. Equatorial Pacific temperature and upper-ocean stratification differences between the 270° and 90° precessional phases. (a, c, e) Longitude–depth sections of ocean temperature differences (270°–90°; shaded, °C) for JJA, DJF, and the annual mean. Contours show the same differences. Red (270°) and blue (90°) dashed lines mark the 20°C isotherm. ΔStrat is the 270°–90° difference in the Cai et al. (2018) stratification index (upper 100 m mean temperature minus temperature at 120 m; 5°S–5°N, 140°E–150°W), with depth intervals adjusted to our model vertical structure. (b, d, f) Corresponding changes in |∂T/∂z|; warm (cool) colors indicate enhanced (reduced) stratification.

Lines 85–98 (Introduction): *"In particular, weakened ENSO variability has been suggested to be associated with a La Niña-like background climate state, characterized by an enhanced East Asian summer monsoon, a strengthened Walker circulation, and intensified eastern Pacific upwelling. More broadly, previous studies have demonstrated that external forcing can reorganize the tropical Pacific mean state through changes in Walker* *circulation strength, warm-pool and ITCZ migration, mixed-layer depth (MLD), wind-stress anomaly structure, and upper-ocean stratification. These mean-state adjustments subsequently regulate the efficiency of coupled ocean–atmosphere feedback that govern ENSO growth, highlighting that ENSO responses to external forcing are fundamentally controlled by the background tropical Pacific state and the associated changes in multiple coupled feedback processes. "*

Lines 245–260 (Results): *"This westward migration of the ITCZ is accompanied by a westward shift of the Walker circulation. The westward displacement of atmospheric circulation strengthens equatorial trade winds in the western Pacific while weakening equatorial westerlies in the Indian Ocean. These changes in surface winds are also associated with a westward displacement of the Indo-Pacific Warm Pool (IPWP), together with a deepening of the western Pacific thermocline and weaker upper-ocean stratification. Geological records indicate enhanced ocean heat content at the 90° precessional phase, supporting a deeper and warmer subsurface thermocline structure within the IPWP region. In the eastern Pacific, the westward-shifted IPWP and intensified trade winds enhance upwelling in the cold tongue region (see Supplementary Figures S5–S7 for atmospheric and oceanic circulation contrasts between the 90° and 270° precessional phases), generating a La Niña-like mean state. This mean-state configuration is consistent with weakened ENSO activity, as demonstrated by our simulations (Figure 1a). "*

After establishing the contrasting stratification characteristics associated with the two extreme ENSO states under different precession phases, we further extend our analysis to all 24 precession experiments to investigate the covariability between upper-ocean stratification and ENSO variability throughout the complete precession cycle.

2. Covariation of upper-ocean stratification and ENSO amplitude

Building on the full precession-cycle simulations, we further examine the co-evolution of upper-ocean stratification and ENSO variability across different precessional phases (Figure R2). The results show that, during the strong ENSO phase of 255°–300°, upper-ocean stratification in the tropical Pacific remains consistently above 1°C and reaches its maximum over the precession cycle near 270°, substantially exceeding the cycle-mean stratification level. In contrast, during the weak ENSO phase interval of 75°–135°, upper-ocean stratification is considerably reduced, coinciding with suppressed ENSO variability. This precession-induced contrast in ocean stratification is fundamentally controlled by the zonal migration of the Indo-Pacific warm pool (IPWP). Near the 90° precession phase, the IPWP and associated deep convection center shift westward, leading to enhanced accumulation of warm water in the western Pacific. The increased western Pacific warm-water volume deepens the equatorial thermocline, pushing subsurface cold water to greater depths and weakening the vertical temperature gradient in the upper ocean, thereby resulting in reduced ocean stratification. In contrast, near the 270° precession phase, the IPWP and deep convection center migrate eastward toward the central Pacific. This eastward displacement reduces warm-water storage in the western Pacific and shoals the equatorial thermocline, allowing subsurface cold water to reside closer to the ocean surface. The enhanced vertical temperature gradient subsequently strengthens upper-ocean stratification.

Following the mechanism proposed by Cai et al., we further suggest that the enhanced upper-ocean stratification during the 270° phase can increase the efficiency with which thermocline anomalies regulate sea surface temperature anomalies, thereby strengthening tropical Pacific air–sea coupling and amplifying the Bjerknes positive feedback, ultimately leading to enhanced ENSO variability. To further clarify the dynamical pathway through which stratification modulates ENSO variability, we next diagnose the thermocline feedback coefficient (α), aiming to quantify how variations in upper-ocean stratification regulate ENSO variability through thermocline-mediated ocean–atmosphere coupling.

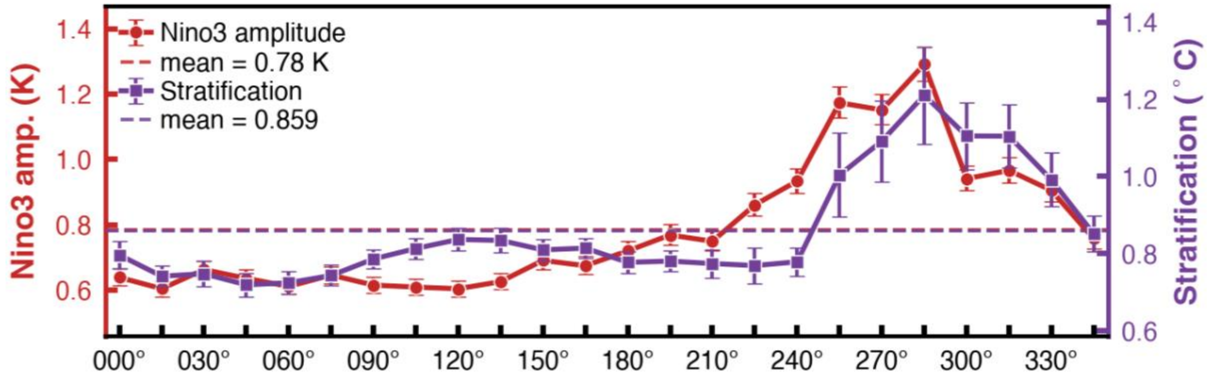

Figure R2. Niño3 amplitude (red; standard deviation of Niño3 SSTA) and upper-ocean stratification index (purple) across the 24 precession experiments. Stratification is the upper-100 m mean temperature minus the temperature at 120 m over 5°S–5°N, 140°E–150°W (Cai et al., 2018; minor reference-depth adjustment). Dashed lines denote multi-experiment means (0.78 K and 0.86°C).

3. Thermocline feedback (α)

To further investigate whether changes in upper-ocean stratification can enhance the coupling efficiency between the thermocline and sea surface temperature, we calculated the thermocline feedback coefficient (α) across the 24 precession experiments. As a key oceanic dynamical component of the Bjerknes feedback mechanism (Bjerknes, 1969; Jin et al., 2006; Lübbecke and McPhaden, 2013; Deppenmeier et al., 2016), α is defined here as the regression coefficient of Niño3 sea surface temperature anomalies onto the peak anomalies of equatorial Z20 depth (see revised Supplementary Material S3 for details). This metric quantitatively characterizes the efficiency with which subsurface ocean dynamical anomalies are transmitted to the surface. Previous studies have demonstrated that this feedback efficiency is strongly regulated by the background state of the tropical Pacific upper ocean, particularly the thermocline structure, mixed-layer depth, and upper-ocean stratification (Cai et al., 2018, 2021; Thirumalai et al., 2024; Tuckman and Yang, 2026).

Across the full precession cycle, α exhibits a pronounced precessional modulation (Figure R3). During the weak-ENSO interval of 75°–135° precession phase, α remains relatively low, indicating reduced efficiency in transferring subsurface ocean dynamical anomalies to the surface. In contrast, α gradually increases after 180° and reaches its maximum around 270°, closely coinciding with the phase interval characterized by enhanced ENSO variability. These results demonstrate that precession-driven strengthening of upper-ocean stratification enhances the sensitivity of sea surface temperature to subsurface ocean anomalies, thereby increasing the efficiency of thermocline–SST coupling and ultimately amplifying ENSO variability through an intensified oceanic branch of the Bjerknes feedback.

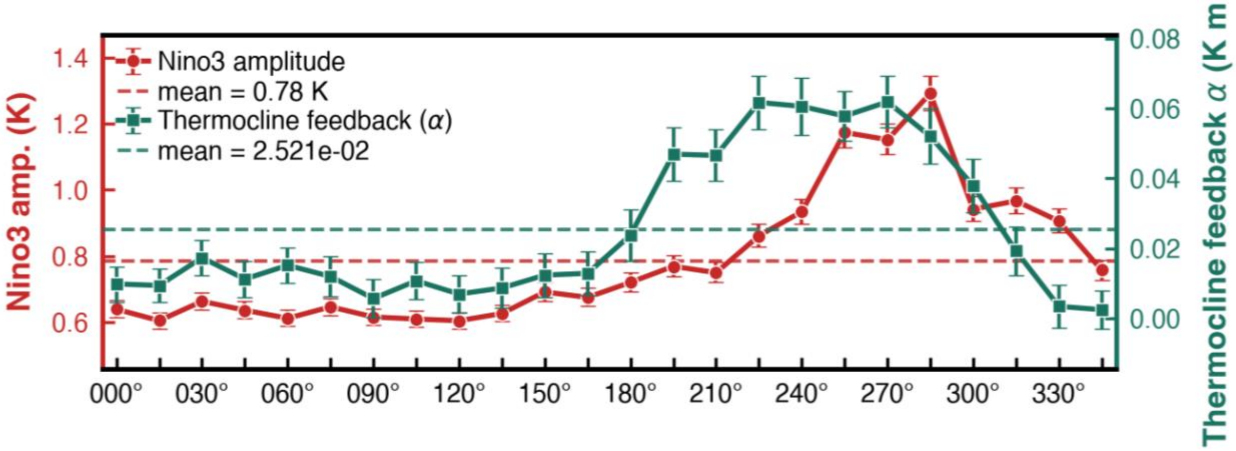

Figure R3. Niño3 amplitude (red) and thermocline feedback α (green; K m⁻¹) across the 24 precession experiments. α is the peak regression of Niño3 SSTA onto Z_{20} anomalies over 5°S–5°N, 140°E–260°E for thermocline leads of 1–6 months. Error bars show 95% confidence intervals. Dashed lines denote multi-experiment means (0.78 K and 0.025 K m^{-1}).

4. Integration with other mean-state and feedback diagnostics

In the revised manuscript, we have incorporated the dynamical role of upper-ocean stratification into a comprehensive physical framework linking tropical Indo-Pacific mean-state changes with ENSO air–sea feedback (Figure 4), thereby revealing the complete dynamical pathway through which precessional orbital forcing regulates ENSO variability. We propose that precession first reorganizes the tropical Indo-Pacific mean climate state through precession-induced asymmetric continental radiative heating and subsequently modulates a suite of tightly coupled mean-state components, including the Walker circulation, equatorial wind field, IPWP position, mixed-layer depth, and upper-ocean stratification. These coordinated mean-state adjustments collectively regulate tropical Pacific air–sea coupling efficiency and ultimately determine the strength of ENSO variability.

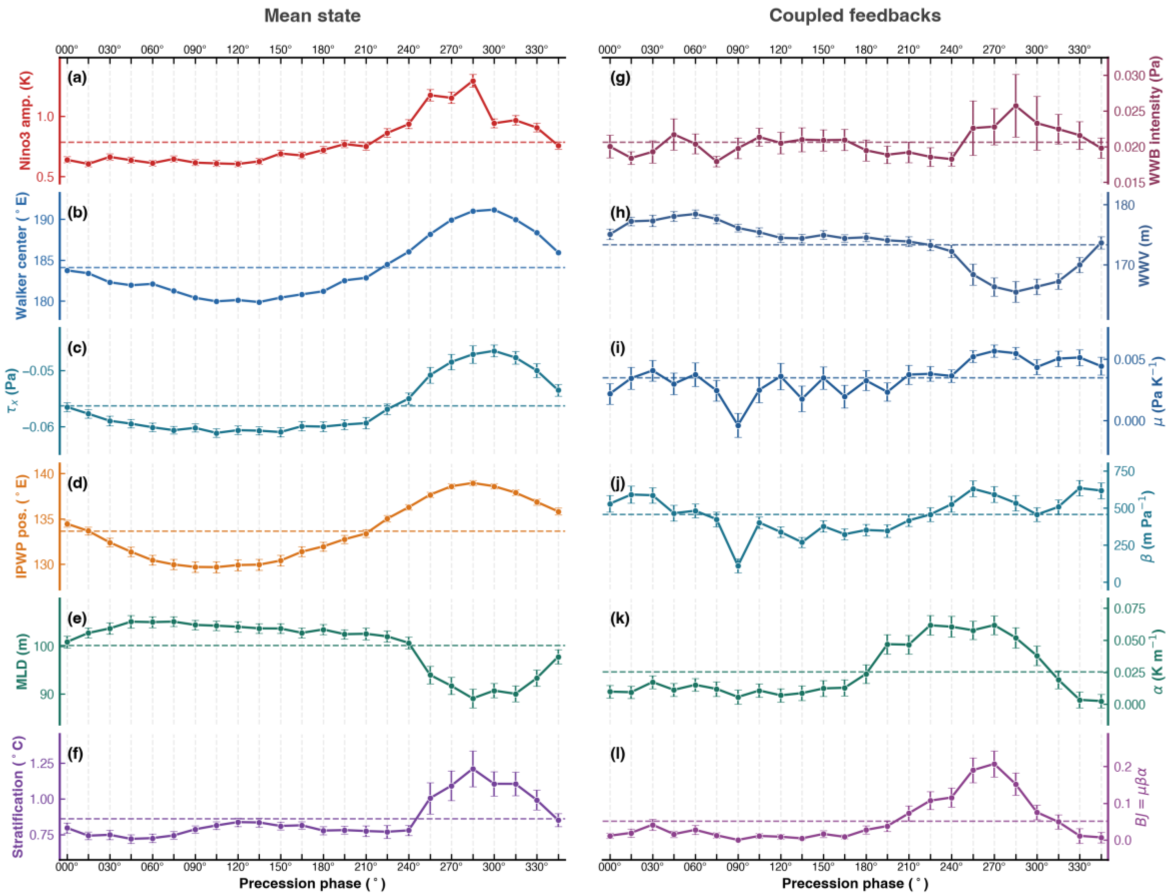

Figure 4. Mean-state and coupled-feedback diagnostics across the 24 precession experiments. Left (mean state): (a) Niño3 amplitude; (b) Walker-circulation center longitude; (c) equatorial zonal wind stress; (d) precipitation-weighted tropical convection centroid (shared ITCZ/IPWP migration surrogate); (e) mixed-layer depth; (f) upper-ocean stratification. Right (coupled feedbacks): (g) WWB intensity; (h) regional WWV proxy based on equatorial Z_{20}; (i) wind feedback μ; (j) ocean dynamical response β; (k) thermocline feedback α; (l) integrated Bjerknes loop gain BJ = μβα. Pearson correlations with Niño3 amplitude are shown in each panel. Strong-ENSO phases coincide with an eastward-displaced Walker circulation and warm pool, weaker trade winds, a shallower mixed layer, enhanced stratification, and stronger Bjerknes-loop efficiency. Definitions: Supplementary Table S3.

Specifically, during the strong-ENSO precession phase interval of 255°–300°, asymmetric continental heating drives an eastward displacement of the Indo-Pacific warm pool and tropical deep convection, accompanied by weakened equatorial trade winds, a shoaling of the mixed layer in the central-western Pacific, reduced warm-water volume, and substantially enhanced upper-ocean stratification. These background-state changes reinforce the Bjerknes positive feedback, with the enhancement of thermocline feedback emerging as the most prominent oceanic contribution, thereby amplifying ENSO variability. In contrast, during the weak-ENSO phase interval of 75°–135°, the tropical mean state exhibits an opposite configuration that collectively suppresses air–sea coupling processes and results in substantially reduced ENSO activity.

Furthermore, our study demonstrates that enhanced upper-ocean stratification and strengthened thermocline feedback represent critical oceanic transmission processes following the reorganization of the tropical Pacific mean state (Cai et al., 2018, 2021). However, these oceanic processes do not independently replace the regulating role of atmospheric mean-state changes; instead, they act synergistically with atmospheric processes, including circulation and wind-field adjustments, highlighting the coordinated evolution and mutual reinforcement among different climate components in controlling ENSO variability.

Lines 316–400 (Results): *"Tropical Pacific mean-state control of ENSO feedback efficiency*

Above, we have demonstrated that precession-induced asymmetric continental heating can reorganize the tropical Pacific mean state, including zonal shifts in the Walker circulation, the ITCZ, the IPWP, and changes in the equatorial thermocline structure. Building on these mean-state changes, we next investigate how the reorganized tropical Pacific background state regulates ENSO variability through changes in air–sea coupling efficiency. Previous studies have shown that ENSO variability depends not only on the magnitude of initial ocean–atmosphere disturbances, but also on the background climate state that determines the efficiency of coupled ocean–atmosphere feedback (molina2026changes, fedorov2001stability, cai2018increased). The growth of ENSO events is primarily governed by the Bjerknes positive feedback (jin2006, bjerknes1969), which consists of three interconnected processes: the atmospheric response of wind stress to SST anomalies (μ), the dynamical response of the thermocline to wind stress anomalies (β), and the thermodynamic conversion of subsurface ocean temperature anomalies associated with thermocline variations into SST anomalies (α). Together, these feedback components form a positive feedback loop that amplifies initial disturbances and promotes the growth of El Niño and La Niña events.

The efficiency of this coupled feedback is highly dependent on the location of the sensitive air–sea coupling region (wang2004understanding). The most effective coupling generally occurs near the eastern edge of the IPWP rather than within its warmest core (guilyardi2009understanding). The warm-pool interior maintains persistent deep convection, where atmospheric convection is frequently active and becomes less sensitive to small SST perturbations because it is constrained by atmospheric stability and moisture availability rather than SST forcing alone. In contrast, the eastern edge of the warm pool is located within an SST range favorable for deep convection (approximately 28°C), where relatively small SST anomalies can induce substantial changes in convection, precipitation, and latent heat release. These atmospheric responses can further modify the Walker circulation and surface wind field, which in turn regulate upper-ocean stratification and MLD and ultimately influence ENSO feedback efficiency (dinezio2012mean, fedorov2020, cai2021changing). Therefore, shifts in the zonal position of the eastern edge of the IPWP relocate the region of maximum air–sea coupling sensitivity. Such changes provide a physical pathway through which external forcing can regulate ENSO variability by modifying coupled feedback efficiency.

The 24 precession simulations reveal a clear orbital modulation of ENSO amplitude (Figure 4). During the strong ENSO phase associated with 255°–300° precession, the Walker circulation and the IPWP shift significantly eastward, accompanied by weakened equatorial easterly wind stress. These atmospheric adjustments are associated with substantial changes in upper-ocean structure, including a shallower mixed layer in the warm pool, enhanced upper-ocean stratification, and a reduced background warm-water reservoir in the western–central Pacific. These changes indicate reduced oceanic thermal inertia, which leads to enhanced sensitivity of SST anomalies to atmospheric perturbations. Meanwhile, WWBs become stronger under this background state. The eastward displacement of the IPWP eastern edge shifts the sensitive air–sea coupling region toward the central Pacific, while the reduced oceanic thermal inertia allows the upper ocean to respond more efficiently to wind perturbations.

Consistent with these mean-state changes, all three components of the Bjerknes feedback increase (Figure 4i–l), with the thermodynamic feedback exhibiting a particularly pronounced enhancement. The atmospheric feedback (μ) increases because SST anomalies more effectively modify atmospheric circulation and wind stress near the displaced warm-pool edge. The dynamical feedback (β) is enhanced because wind stress anomalies more efficiently perturb thermocline depth. In addition, the shallower thermocline and stronger upper-ocean stratification increase the efficiency of converting subsurface ocean temperature anomalies associated with thermocline variations into surface warming or cooling, leading to enhanced thermodynamic feedback (α). Therefore, the combined Bjerknes feedback gain (BJ = μβα) reaches its maximum near 270° precession. The *strengthened positive feedback loop amplifies initial ocean–atmosphere disturbances and produces larger ENSO variability.*

In contrast, ENSO variability is substantially reduced during the precessional phase between 75°–135°. The standard deviation of Niño3 SST anomalies reaches its minimum, while the Walker circulation and IPWP remain shifted westward. Stronger background easterly winds maintain a more stable cold-tongue structure and inhibit the growth of SST anomalies, while the warm pool upper ocean exhibits a deeper mixed layer, weaker stratification, and a larger thermal reservoir. Under these conditions, the efficiency of air–sea coupling decreases. The westward displacement of the IPWP eastern edge reduces the sensitivity of atmospheric convection and wind stress to SST anomalies, weakening the atmospheric feedback (μ). The reduced response of the thermocline to wind forcing decreases the dynamical feedback (β), while the deeper thermocline and weaker stratification inhibit the transfer of subsurface ocean anomalies to the surface, reducing the thermodynamic feedback (α). Consequently, the combined Bjerknes feedback gain (BJ = μβα) reaches a minimum, preventing initial disturbances from undergoing sustained amplification and resulting in weaker ENSO variability.

Together, these results demonstrate that precessional forcing does not regulate ENSO variability simply by shifting the tropical Pacific toward a mean El Niño-like or La Niña-like state. Instead, external forcing (like precession) modifies the background climate state, including the Walker circulation (dinezio2013detectability, fedorov2020), IPWP position (thirumalai2024future, molina2026changes, pontes2022mid), surface wind field, mixed-layer structure, and upper-ocean stratification (cai2018increased, tuckman2026rise), thereby regulating the efficiency of tropical Pacific air–sea coupling. These mean-state adjustments collectively modulate the three components of the Bjerknes feedback (μ, β, and α). In our simulations, enhanced upper-ocean stratification plays a particularly important role by strengthening the thermodynamic feedback (α), while the concurrent increase in atmospheric wind feedback (μ) further amplifies the total Bjerknes feedback efficiency. Together, these processes explain the enhanced ENSO variability near the 270° precession phase by establishing a background state with more efficient ocean–atmosphere coupling."

Lines 474–526 (Discussion): *"A key advance of this study is the clarification of the physical pathway through which precessional forcing reorganizes tropical mean-state conditions. Previous studies have attributed the reduced ENSO activity during the Early-Middle Holocene to a suite of tropical Pacific background-state changes, including intensified Asian summer monsoon circulation (liu2000modeling), an enhanced zonal Walker circulation (white2018dampened, dang2020pacific), stronger equatorial trade winds (pausata2017greening), increased eastern Pacific upwelling (white2018dampened, lu2019prominent), a westward-displaced ITCZ (pontes2022mid), an intensified zonal SST gradient (sadekov2013palaeoclimate), and enhanced subtropical warm-water subduction into the equatorial thermocline (chen2019towards, lu2025enhanced). However, these atmospheric and oceanic mean-state variables are strongly coupled and co-vary under the influence of multiple external forcings (dinezio2012mean, wang2024pdo), making it challenging to isolate the direct role of precession and determine the pathway linking orbital forcing to tropical Pacific reorganization. Based on high-resolution simulations spanning a complete precession cycle, we demonstrate that these previously identified, seemingly independent mean-state adjustments originate from a common dynamical source: precession-induced hemispheric asymmetric continental heating. This mechanism establishes a direct physical connection between orbital insolation forcing and tropical Pacific mean-state evolution, providing a unified explanation for how precession affects ENSO variability.*

Furthermore, our results demonstrate that external forcing does not regulate ENSO variability simply by shifting the mean climate state toward an El Niño-like or La Niña-like background condition (okumura2011proposed, dinezio2012mean). Instead, ENSO variability is primarily controlled through changes in the efficiency of ocean–atmosphere coupling within the tropical Pacific mean state. This mechanism shares fundamental similarities with ENSO responses under anthropogenic warming. Previous studies suggest that greenhouse warming may intensify ENSO variability by strengthening upper-ocean stratification (cai2018increased, tuckman2026rise), promoting an eastward expansion of the IPWP (thirumalai2024future, molina2026changes), weakening the Walker circulation and equatorial trade winds (dinezio2011response, dinezio2013detectability), and modifying the structure of wind stress anomalies (stuivenvolt2025widening), thereby enhancing the Bjerknes feedback and *increasing the intensity and/or frequency of extreme ENSO events (dinezio2010reconciling). Although precessional forcing and anthropogenic greenhouse forcing differ fundamentally in their external origins, both influence ENSO through a common dynamical pathway: reorganizing the tropical Pacific background state and modifying the efficiency of coupled ocean–atmosphere feedback (dinezio2012mean, fedorov2020, cai2021changing). Under the 270° precession configuration, eastward migration of the IPWP and Walker circulation, decreased western–central Pacific WWV, a shallower mixed layer and intensified upper-ocean stratification reduce the thermal inertia of the western Pacific warm pool. This allows modest climatic perturbations to initiate stronger Bjerknes feedback and consequently promotes heightened ENSO variability. This explains why ENSO variability reaches its maximum amplitude under the modern-like precession configuration relative to other phases within the simulated precession cycle. Therefore, our results provide a broader perspective for understanding how variations in climate mean states regulate ENSO variability across different external forcing scenarios.*

In summary, this study identifies precession-driven asymmetric continental thermal forcing as a fundamental driver of tropical Indo-Pacific mean-state reorganization and further demonstrates that changes in IPWP position, upper-ocean stratification, thermocline feedback, and the overall Bjerknes feedback system constitute key dynamical pathways through which ENSO variability responds to background climate changes. The proposed mechanism, linking orbital forcing to mean-state adjustment, air–sea coupling efficiency, and ENSO amplitude modulation, advances our understanding of astronomical-scale ENSO evolution and provides a physically based framework for interpreting ENSO responses under future climate change scenarios and associated changes in climate extremes."

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