

Ocean thermal inertia under net-zero commits the tropical Pacific to a persistent regime shift

Aditya Sengupta

`aditya.sengupta@student.unimelb.edu.au`

School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Melbourne, VIC, Australia <https://orcid.org/0000-0003-2721-3818>

Andrew King

University of Melbourne <https://orcid.org/0000-0001-9006-5745>

Josephine Brown

University of Melbourne <https://orcid.org/0000-0002-1100-7457>

Nicola Maher

Australian National University <https://orcid.org/0000-0003-3922-9833>

Mandy Freund

University of Melbourne <https://orcid.org/0000-0002-8839-5494>

Tilo Ziehn

CSIRO Oceans and Atmosphere <https://orcid.org/0000-0001-9873-9775>

Ellie Ong

School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Melbourne, VIC, Australia

Andréa Taschetto

University of New South Wales <https://orcid.org/0000-0001-6020-1603>

Shayne McGregor

Monash University <https://orcid.org/0000-0003-3222-7042>

Andrea Dittus

University of Reading <https://orcid.org/0000-0001-9598-6869>

Article

Keywords: ENSO, Tropical Pacific, net-zero, ZECMIP, ITCZ, Ocean circulation

Posted Date: April 24th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9378775/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: There is **NO** Competing Interest.

Version of Record: A version of this preprint was published at Communications Earth & Environment on October 13th, 2026. See the published version at <https://doi.org/10.1038/s43247-026-04082-x>.

Ocean thermal inertia under net-zero commits the tropical Pacific to a persistent regime shift

Aditya Sengupta^{1,2}, Andrew D. King^{1,2}, Josephine R. Brown^{1,2}, Nicola Maher^{3,2}, Mandy B. Freund^{1,2}, Tilo Ziehn⁴, Ellie Q. Y. Ong^{5,2}, Andréa S. Taschetto^{6,2}, Shayne McGregor^{5,2}, and Andrea Dittus⁷

¹School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Melbourne, Kulin nations, Australia

²ARC Centre of Excellence for Weather of the 21st Century, Australia

³Research School of Earth Sciences, The Australian National University, Ngunnawal country, Canberra, ACT, Australia

⁴CSIRO Environment, Aspendale, Kulin nations, Australia

⁵School of Earth, Atmosphere, and Environment, Monash University, Clayton, Kulin nations, Australia

⁶Climate Change Research Centre, University of New South Wales, Sydney, New South Wales, Australia

⁷National Centre of Atmospheric Science, Department of Meteorology, University of Reading, Reading, United Kingdom

Corresponding author:

Aditya Sengupta

Email address: aditya.sengupta@student.unimelb.edu.au

Abstract

The tropical Pacific plays a pivotal role in global climate. Changes in its mean state and El Niño–Southern Oscillation (ENSO) could significantly alter regional hydroclimates, causing major economic and societal impacts, yet its response to different emission pathways remains poorly constrained. Here, we assess changes in the mean state and ENSO under high-emission and net-zero scenarios using climate model simulations spanning centennial to millennial timescales. Under transient warming, the tropical Pacific exhibits an El Niño–like mean state shift accompanied by increased ENSO amplitude. Following emission cessation, this altered mean state persists as ENSO variability and frequency of extreme El Niño events remain elevated for centuries. This shift sustains El Niño–like rainfall anomalies despite declining atmospheric CO₂. These findings indicate that key aspects of tropical Pacific climate change are effectively irreversible, implying that net-zero emissions may slow further change but are insufficient to restore pre-industrial conditions.

Keywords: ENSO; Tropical Pacific; net-zero; ZECMIP; ITCZ; Ocean circulation

1 Introduction

Tropical Pacific climate variability drives global impacts across time-scales, including the modulation of global mean temperature [1, 2], high-impact weather [3], and adverse socio-economic effects [4]. These impacts are largely associated with El Niño-Southern Oscillation (ENSO), a leading mode of interannual climate variability characterised by eastern Pacific warming/cooling and shifts in tropical convergence zones [5] during its two active phases, El Niño and La Niña. Understanding how ENSO evolves in a changing climate is critical, but there is little consensus on the direction and magnitude of ENSO changes [6]. Most studies suggest an increase in the ENSO amplitude, in response to anthropogenic warming [5, 7, 8], while some studies suggest either non-robust changes [9] or robust decrease in ENSO amplitude, [10–12] with these uncertainties largely stemming from unforced variability [9, 11] and model differences [13].

Unlike ENSO changes, there is broad inter-model agreement on changes in the tropical Pacific mean state, often represented by the west-minus-east equatorial Pacific zonal temperature gradient (ZTG). Most models project a weakening ZTG with faster warming in eastern equatorial Pacific [14, 15], implying a more “El Niño-like” mean state. However, confidence in these projections is limited due to a discrepancy of models with observations, which show a strengthening ZTG in recent decades [14–16]. This mismatch raises concerns about the fidelity of Earth system models (ESMs), given persistent model biases in simulating tropical Pacific processes [16–18] and their inability to accurately represent convective cloud feedbacks and mesoscale ocean eddies [19].

The model-observation mismatch in the ZTG response may be explained by several concordant physical and dynamical mechanisms [14, 15]. These mechanisms, which include: internal variability on decadal timescales [20–22]; transient ocean dynamical thermostat cooling [17, 23]; short-lived climate forcings such as aerosols and stratospheric ozone [24–26]; and remote impacts of Southern Ocean cooling [27, 28], can temporarily strengthen ZTG but are expected to weaken over time. On the other hand, mechanisms that weaken ZTG: oceanic tunnel [23]; Southern Ocean warming [29, 30]; and differential evaporative damping [15, 31], are likely to amplify, implying that the forced weakening of ZTG will likely emerge in the 21st century [14, 15, 30, 32]. This suggests that the apparent model-observation mismatch may be due to factors such as internal variability dominating historical trends, with future change expected to favour ZTG weakening. Consistent with this, McGregor et al. [33] show that CMIP6 models with smaller tropical Pacific mean state biases better match historical ZTG trends and project greater ZTG weakening.

Changes in ENSO and ZTG have been extensively studied under transient and abrupt CO₂ forcing experiments. However, their evolution under low-emission pathways, particularly net-zero emission futures that are under-represented in the Coupled Model Intercomparison Project (CMIP), remains largely unexplored [34]. Studies using idealised CO₂ removal experiments suggest the presence of long-term hysteresis in ENSO characteristics [35–37], but such scenarios do not align with the currently limited deployment of large-scale CO₂ removal technologies [38, 39]. This motivates a focused assessment of tropical Pacific evolution under policy-relevant net-zero emission scenarios across different warming levels [40]. The climate system will continue to evolve even after emissions cease [41–43], due to ocean memory and slow circulation processes, with impacts of cumulative emissions persisting for centuries, raising the possibility of long-lived or effectively irreversible changes in ENSO and the tropical Pacific mean state.

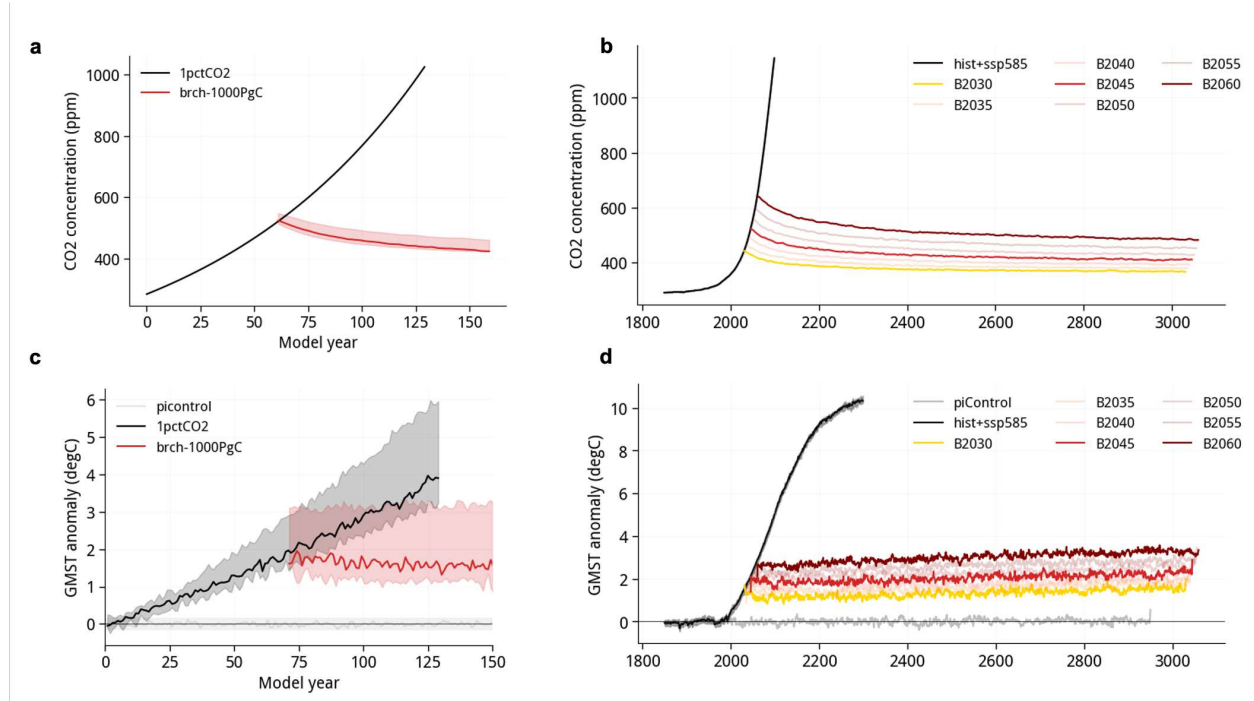


Figure 1. CO₂ concentration and GMST changes in ZECMIP and ACCESS-ESM1-5 net-zero experiments. **a**, CO₂ concentration changes in the 1pctCO₂; brch-1000PgC emission cessation scenario in the ZECMIP Tier 1 experiments. **b**, CO₂ concentration changes in ACCESS-ESM1-5 historical (1850–2014), SSP5-8.5 (2015–2300) runs and seven 1000-year long net-zero branching runs separated by an interval of 5 years. The net-zero branching runs B2030, B2045 and B2060 are shown in bold colours. **c**, **d**, Same as **a**, **b** but for GMST anomaly changes. The gray solid line in **c** indicates the multimodel ensemble average GMST anomaly in piControl runs, while the gray shading represents the 10th–90th percentile range across the multimodel ensemble. Note that the time on the horizontal axis in **d** does not represent the piControl time index, which varies from 0–1000. The gray solid line in **d** indicates the GMST anomaly evolution in the ACCESS-ESM1-5 piControl run.

Results and Discussion

Centennial-scale post net-zero changes in tropical Pacific

Here, we analyse the implications of the slowly evolving Earth system components on ENSO and ZTG by first using the Zero Emissions Commitment Model Intercomparison Project (ZECMIP) [44] tier 1 experiment. Nine ESMs simulate branching from the 1% CO₂ (1pctCO₂) transient run with CO₂ emissions set to zero at the point of 1000PgC of cumulative emissions (brch-1000PgC; Fig.1a) leading to a stabilisation of global mean surface temperature (GMST) at about 2°C above preindustrial (Fig.1c) with some inter-model differences (Supplementary Fig.1). The changes in ENSO amplitude in the transient 1pctCO₂ run are highly model dependent and non-monotonic (Supplementary Fig. S2). Seven out of nine models suggest an ENSO amplification in the 1pctCO₂ transient run, while others show non-significant changes (Supplementary Fig. S2). The multi-model median response indicates a slight increase in ENSO amplitude (Fig.2a,b). Post emission cessation, in the branching run, six out of nine models and the ensemble median shows a persistence of elevated ENSO amplitude (Supplementary Fig. S2 and Fig. S2a,b). ZTG response in the transient run is consistent across all models (Supplementary Fig. S3), showing a weakening (El Niño–like mean state change) which also persists for decades after emission cessation (Fig.2c,d). In the three models that ran two additional branching experiments at low (750PgC) and high (2000PgC) levels of cumulative emissions, the tropical Pacific changes are more prominent at the highest level, often showing a continuous ZTG weakening post emission cessation particularly in the UKESM1-0-LL model (Supplementary Fig. S3).

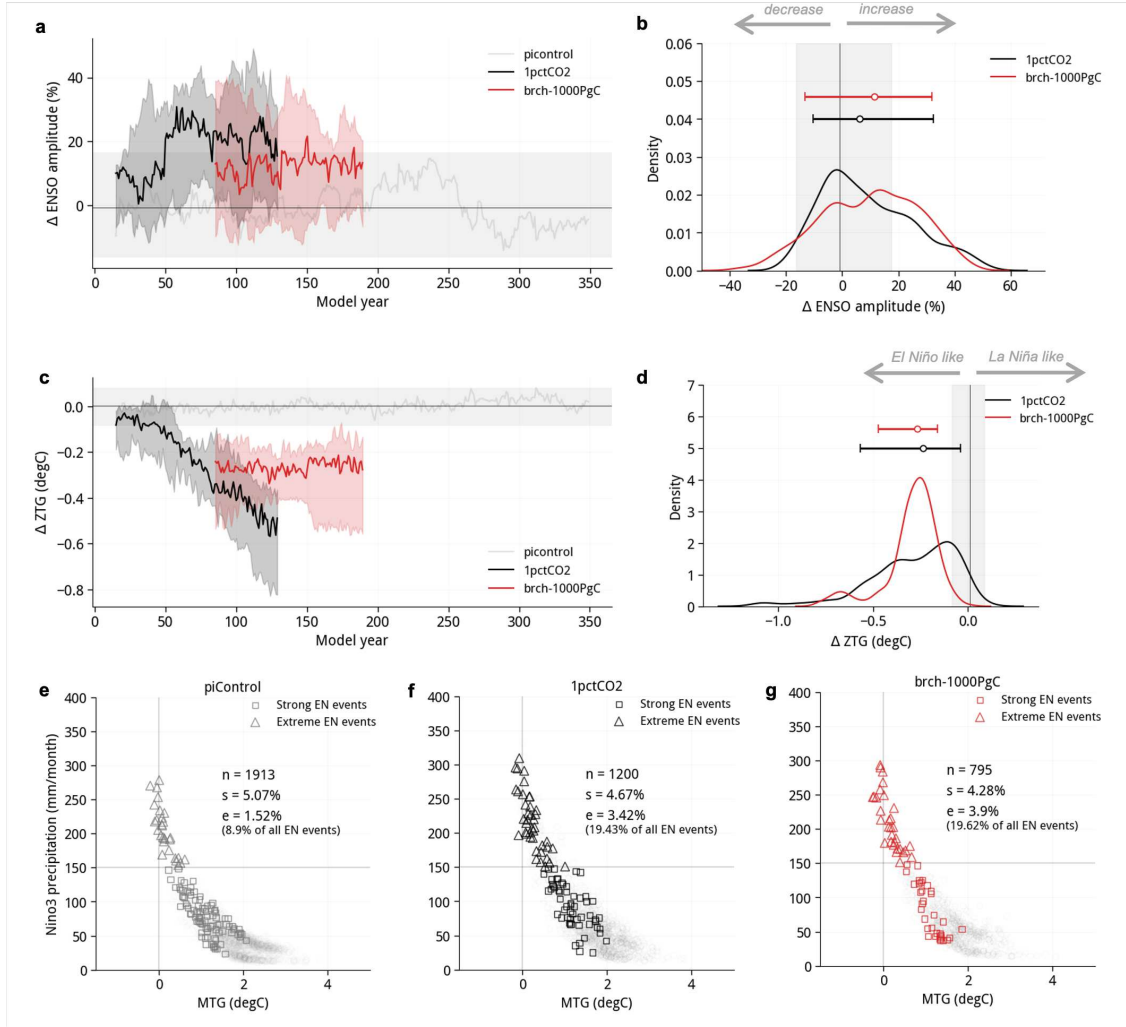


Figure 2. Persistence of elevated ENSO amplitude, weakened ZTG and extreme El Niño events under zero CO₂ emissions in ZECMIP. **a**, Changes in ENSO amplitude, calculated as the 30-year rolling standard deviation of Niño3 index, in the 1pctCO₂ (black) and ZECMIP brch-1000PgC (red) experiments. The thick line represents the median across the model ensemble ($n=9$) and the shading represents the 10th–90th percentile range of the model ensemble. **b**, The kernel density estimate of ENSO amplitude across the model ensemble for the 1pctCO₂ and ZECMIP branching experiments. The inset whisker plots represent the median, 10th and 90th percentile of the temporal distributions. The gray line represents the changes in ENSO amplitude in the piControl experiment. The thin black line is the piControl average across time and model ensemble, while the grey shading represents the 10th–90th percentile range. **c**, **d**, Same as **a**, **b** but for the 30-year rolling average of the ZTG anomaly. **e–g**, Relationship between meridional temperature gradient (MTG) and precipitation in the Niño3 region (see Methods) of piControl (**e**), 1pctCO₂ (**f**) and ZECMIP brch-1000PgC (**g**) experiments. The variables n , s and e represent the sample size, strong and extreme El Niño events, as a percentage of all ENSO events respectively. The value of e in brackets represents the extreme El Niño events as a percentage of only El Niño events. The horizontal gray line represents the 150 mm/month threshold used to define extreme El Niño events.

To investigate the influence of the background mean state and ENSO amplitude changes on the frequency of extreme El Niño events, we calculate the relationship between the meridional temperature gradient (MTG) and precipitation in the east equatorial Pacific in piControl, 1pctCO₂ and brch-1000PgC runs across all models (see Methods). This relationship is a good proxy for measuring extreme El Niño event frequency [45, 46] because during an El Niño event, a warmer eastern equatorial Pacific leads to weakened MTG and ZTG, associated with an equatorward shift of the Inter-tropical Convergence Zone (ITCZ), thereby increasing convection in eastern equatorial Pacific. We find a two-fold increase in extreme El Niño events in the transient 1pctCO₂ runs (Fig.2e,f) owing to increased precipitation variability in eastern equatorial Pacific and a weakening of the MTG due to enhanced warming in eastern equatorial Pacific, which aligns with the

67 results of Cai et al. [45]. Post net-zero, these changes persist (Fig.2g) owing to a sustained net-equatorward
68 shift of the tropical convergence zones with continuous warming in eastern equatorial Pacific (Supplementary
69 Fig. S4), similar to the findings of Cai et al. [5] and Liu et al. [47].

70 **Millennial-scale post net-zero changes in tropical Pacific**

71 To better isolate the long-term impacts of anthropogenic forcing on ENSO amplitude, ZTG and causes therein,
72 we use seven 1000-year long bespoke net-zero CO₂ emission scenarios run with the Australian Earth System
73 model, ACCESS-ESM1-5 [40, 43]. These scenarios branch from the transient SSP5-8.5 scenario between
74 2030–2060 (at 5-year intervals) and show a slow warming trend even after emissions cease (Fig.1b,d). We
75 use three of these simulations: early (B2030), middle (B2045) and late (B2060) branching runs, to investigate
76 the implications of the timing of achieving net-zero this century [40, 43]. This modelling framework provides
77 sufficient data to generate statistically robust analyses of the long-term implications of forced changes in the
78 Earth system after emission cessation in comparison to an equivalent 1000-year long piControl run without
79 any external forcing.

80 Under long-term transient warming (SSP5-8.5 scenario), ENSO amplitude initially increases along with
81 a weakening ZTG (Fig.3a–d). However, post-2100, ENSO amplitude decreases to below the piControl
82 range (Fig.4b,c), even though ZTG continues to weaken. These results align with previous studies [48, 49]
83 indicating a shift towards a more El Niño–like mean state. Similar to the ZECMIP results, our bespoke
84 runs also exhibit persistent long-term weakening in ZTG, and a persistence in the amplification of ENSO
85 amplitude on centennial timescales (Fig.3 and Fig.4d).

86 Based on our thresholds for extreme El Niño event frequency analysis (see Methods), we do not find
87 any events in the piControl run (Fig.3e), but under transient warming, extreme El Niño events increase
88 significantly (Fig.3f–h). Post net-zero, the extreme El Niño events reduce in frequency but persist (Fig.3i–k).
89 All these changes increase incrementally at higher warming levels, with the largest changes in the delayed
90 B2060 run associated with the strongest mean state shift. Under transient warming, the 30–year period
91 centred at the branching year of 2060, represents a climate where 36% of all El Niño events are extreme
92 (see Fig.3f), across the 40 member ensemble. Post net-zero B2060, this number is smaller (27%) but still
93 significantly larger than piControl (see Fig.3i). At lower warming levels, the magnitude of the increase in
94 extreme El Niño events is smaller, particularly for B2030 and its transient counterpart, where the extreme El
95 Niño events are roughly 2–4% of all events. This adds to the body of evidence demonstrating the importance
96 of rapid and substantial climate mitigation, in this case to prevent a non-linear increase in extreme El Niño
97 occurrences for many centuries [37].

98 Our findings of an amplification in ENSO amplitude under stabilisation differ from Callahan et al. [11]
99 which found a robust decrease in ENSO amplitude and a weakened ZTG in millennial-length simulations
100 with fixed atmospheric carbon dioxide concentrations following an abrupt change (e.g. doubling, quadrupling,
101 etc.). Their analysis is at very high atmospheric CO₂ concentrations, relative to our bespoke net-zero runs
102 (Fig.1a,b), and is more comparable to the ENSO amplitude response under the extended SSP5-8.5 scenario.
103 The differences in the responses to equilibration at low or high atmospheric CO₂ highlight the complex and
104 nonlinear relationship between ENSO amplitude and mean state. We believe that the nonlinearity arises due
105 to a time-varying response of ENSO amplitude to anthropogenic forcing, as highlighted in previous work [13].
106 During moderate warming, a weakened ZTG can enhance ENSO amplitude by reducing convective thresholds
107 in the eastern equatorial Pacific [14, 15, 46, 50]. In contrast, under sustained or extreme CO₂ forcing, further

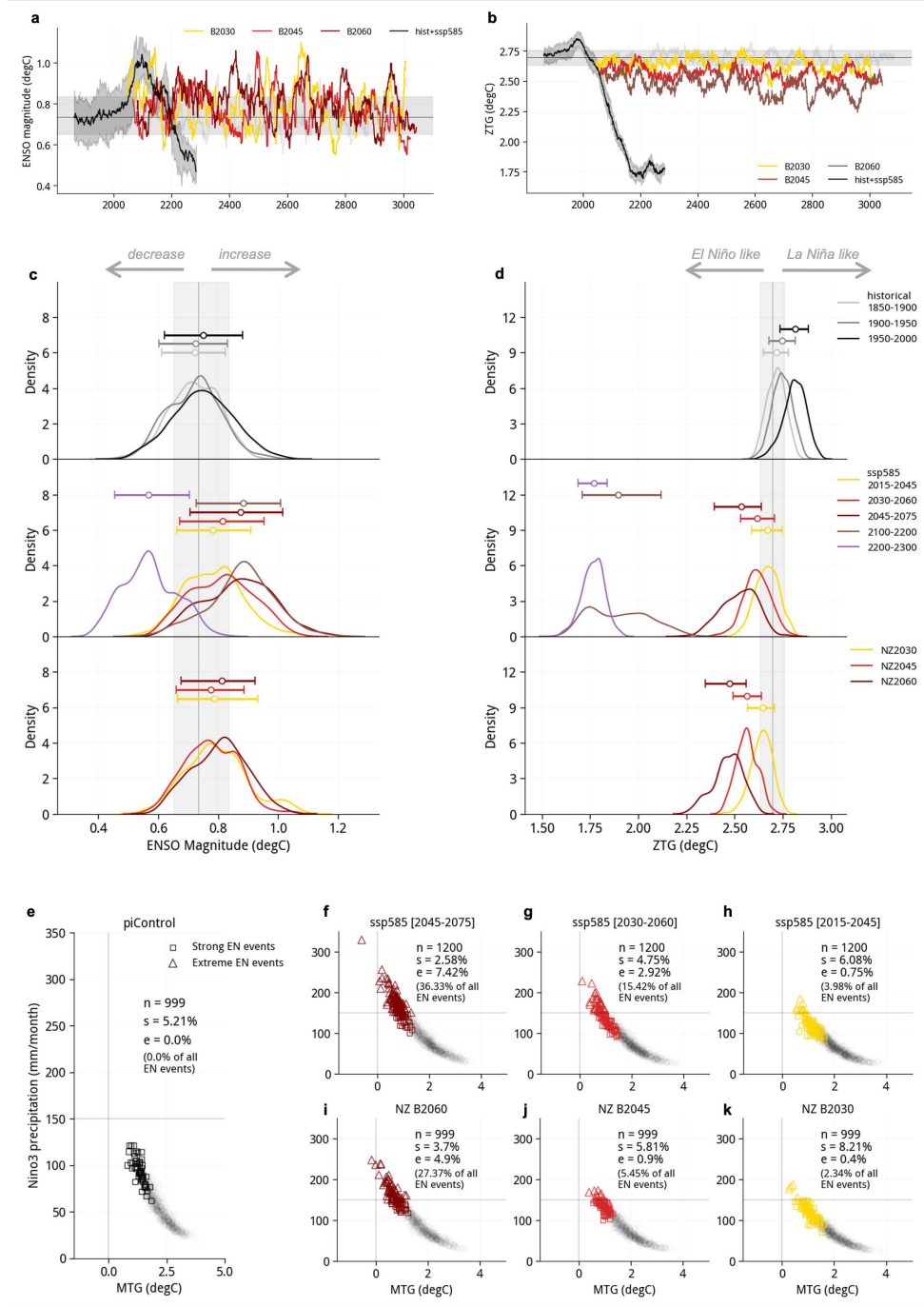


Figure 3. Persistence of elevated ENSO amplitude, weakened ZTG and extreme El Niño events under zero CO₂ emissions at different warming levels in ACCESS-ESM1-5 net-zero runs. **a, b**, Changes in ENSO amplitude (**a**) and ZTG (**b**) in SSP5-8.5 (black), and branching runs: B2030 (gold), B2045 (red) and B2060 (maroon). The thick black line represents the median for SSP5-8.5, while shading represents the 10th–90th percentile range across the 40-member large ensemble. The gray line represents the ENSO amplitude and ZTG anomaly in the piControl experiment. The thin black line is the piControl average across time and model ensemble, while the grey shading represents the 10th–90th percentile range. Note that the time on the horizontal axis in **a** and **b** does not represent the piControl time index, which varies from 0–1000. **c, d**, The kernel density estimate of ENSO amplitude (**c**) and ZTG (**d**) across the 40-member model ensemble at different time-slices for both SSP5-8.5 and branching runs. The inset whisker plots represent the median, 10th and 90th percentile of the distributions. **e–k**, Relationship between MTG and precipitation in the Niño3 region in the piControl (**e**), SSP5-8.5 experiment (**f–h**) and net-zero branching runs (**i–k**) for different time slices. The variables n , s and e represent the sample size, strong and extreme El Niño events, as a percentage of all ENSO events respectively. The value of e in brackets represents the extreme El Niño events as a percentage of only El Niño events. The horizontal gray line represents the 150 mm/month threshold used to define extreme El Niño events.

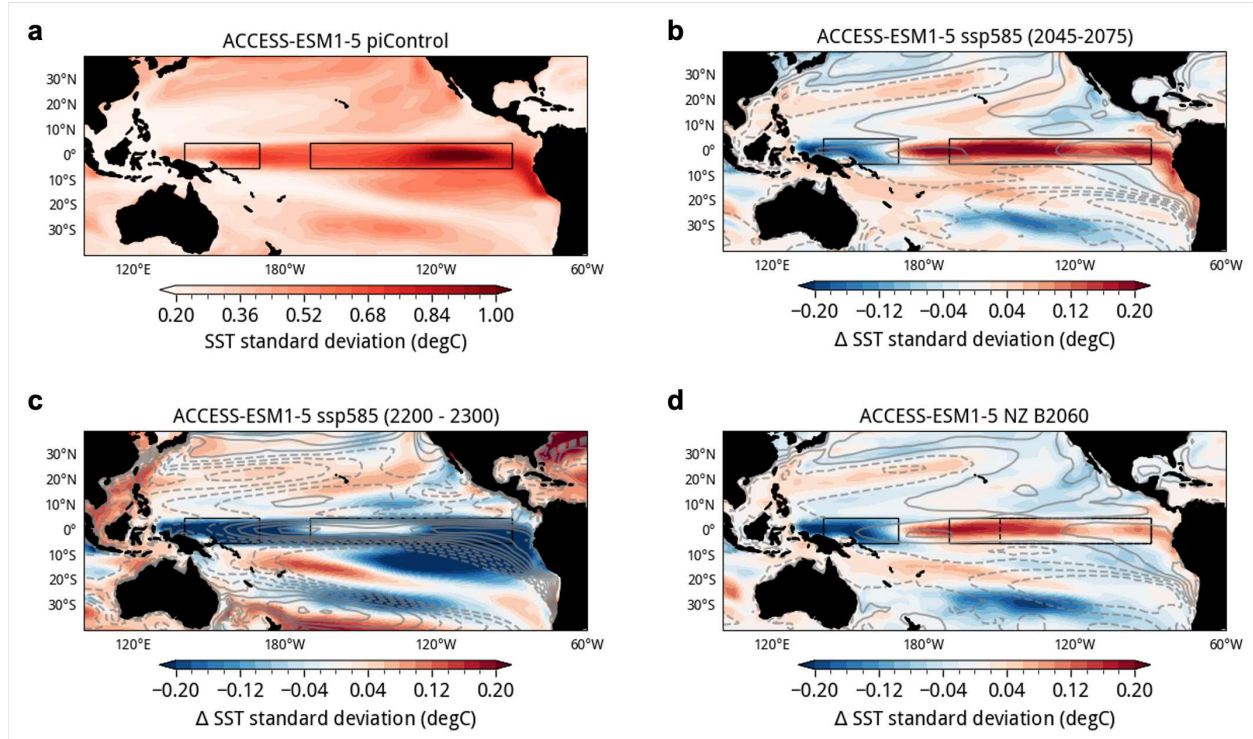


Figure 4. SST variability changes in the tropical Pacific under sustained long term transient warming and post net-zero scenarios using ACCESS-ESM1-5. **a**, SST variability in the tropical Pacific in the ACCESS-ESM1-5 1000-year long piControl run. The black boxes represent the West and East equatorial Pacific regions used for calculating the value of ZTG. **b**, **c**, Changes in the SST variability, averaged across the 40 member ensemble under transient warming in SSP5-8.5 scenario, during 2045–2075 and 2200–2300. **d**, Change in the SST variability under emission cessation in post net-zero 1000-year long branching run B2060. The solid (dashed) gray contours represent the positive (negative) relative SST anomalies in the tropical Pacific. The relative anomalies were calculated by subtracting the global average SST anomaly from the SST anomaly at each grid point.

ZTG weakening may suppress ENSO growth rates and variability through collapsed upwelling or weakened thermocline feedbacks [10, 11, 48, 49, 51].

Evidence from paleoclimate modelling and proxy reconstructions also point to a nonlinear sensitivity of ENSO amplitude to tropical Pacific background mean state across climate regimes [52, 53], with a strengthened (weakened) ZTG and low (elevated) ENSO amplitude under glacial (warmer) conditions [54], but a weakened amplitude and ZTG under more extreme warm tropical Pacific mean state conditions [52, 55, 56]. These studies suggest that ENSO amplitude does not respond monotonically to mean state change. Our results place net-zero stabilisation scenarios within this broader nonlinear framework, indicating that moderate warming followed by emission cessation may lock in a weakened ZTG and sustain elevated ENSO variability for centuries, even without extreme CO₂ concentrations.

Constraints on recovery and persistence of a tropical Pacific regime shift

Multiple competing mechanisms can influence ZTG and ENSO amplitude under transient greenhouse warming, including changes in atmospheric stability, ocean stratification, and large-scale circulation adjustments [5, 14, 15]. As a result, it is difficult to attribute changes to a single driver during the warming phase. However, the persistence of mean-state anomalies following emission cessation suggests that slower components of the climate system impose additional constraints on the long-term recovery. Here, we discuss these constraints and the potential mechanisms through which the tropical Pacific mean state and variability evolve under net-zero.

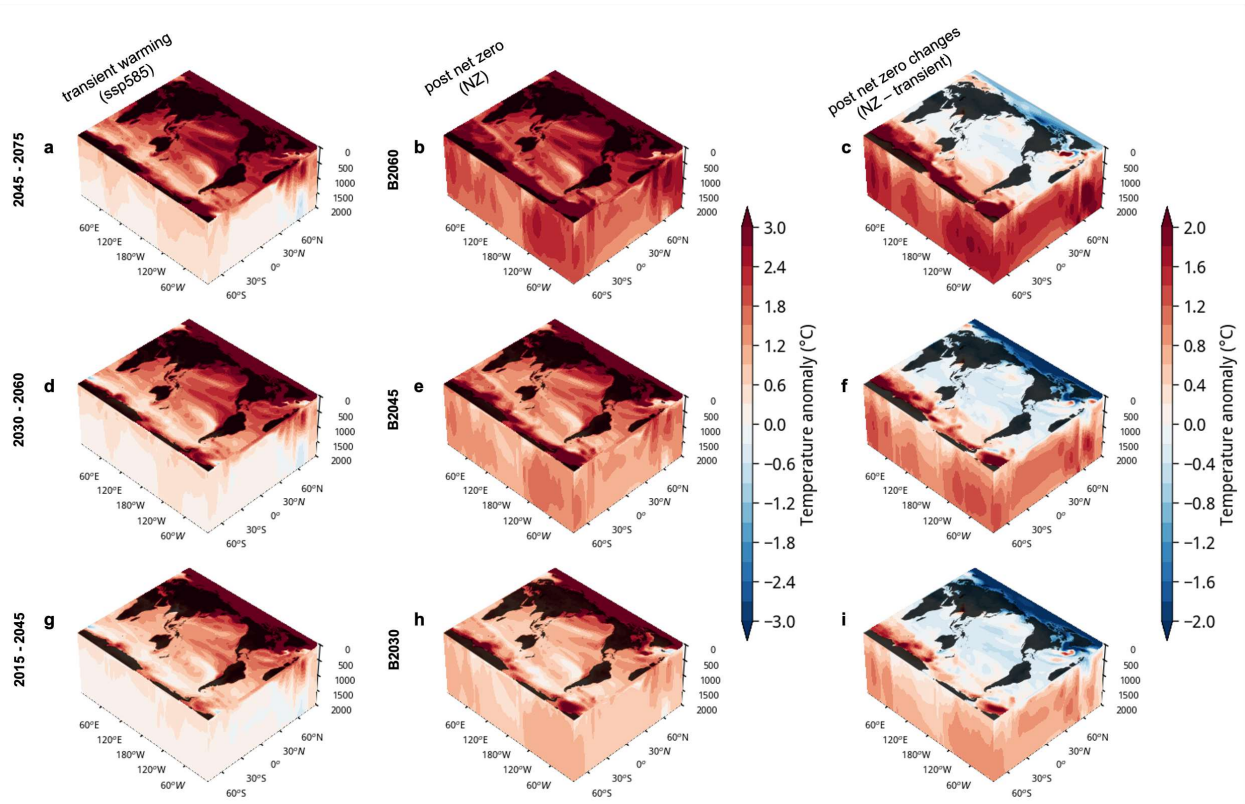


Figure 5. Long term sea surface, deep ocean and Southern Ocean temperature change in ACCESS-ESM1-5 net-zero runs. **a–c**, SST, Southern Ocean potential temperature and deep ocean potential temperature anomalies under transient warming, compared to historical, during the 30-year climatology centred at year 2060, i.e. 2045–2075 (**a**), net-zero branching run B2060 (**b**) and the changes post net-zero in B2060 run compared to transient warming (**c**). Warming in the cross and side sections is averaged over the 40°S–80°S latitude band and 0°–360° longitude band, respectively. **d–f**, **g–i**, Same as **a–b** but for transient warming period 2030–2060; net-zero B2045 and transient warming period 2015–2045; net-zero B2030, respectively.

A prominent feature of post-net-zero simulations is the continued warming of the Southern Ocean and deep ocean, even though surface temperatures in the Northern Hemisphere stabilise or decrease (Fig.5 and Supplementary Figs. S5 and S6). This delayed Southern Hemispheric warming leads to a reduction in the inter-hemispheric temperature gradient and is accompanied by a sustained net-equatorward shift of the ITCZ and South Pacific Convergence Zone (SPCZ) (Fig.6; Supplementary Fig.7a,b). Coherent changes in mean sea-level pressure (MSLP) and surface winds (Supplementary Fig. 8) indicate hemispherically asymmetric changes in the position and strength of subtropical high-pressure systems under transient warming and post net-zero. Previous studies have shown that these changes are associated with cross-equatorial flow, due to the south–north thermal contrast driven by Southern Ocean heat uptake [57, 58].

In addition to the persistent ocean warming, we also find a regime shift in tropical Pacific convergence zones under post-net-zero conditions. During transient warming, the convergence zones shift equatorward, leading to an increase in the tropical Pacific convective area (Fig.6h) and the SST threshold for convection increases (Supplementary Fig.7c). As a result, the eastern equatorial Pacific remains closer to deep convection, relative to a pre-industrial climate, lowering the effective threshold for strong El Niño events. These changes persist after emissions cease, and are particularly strong in the B2060 branching run. An equatorward migration of convergence zones has previously been shown to be associated with enhanced eastern Pacific variability in past warmer climates [52]. Such shifts have also been shown to persist under CO₂ removal scenarios because of continued deep-ocean and Southern Ocean warming [36, 47, 59]. Our results support the evidence that CO₂ mitigation does not guarantee a recovery of tropical convection patterns. We also

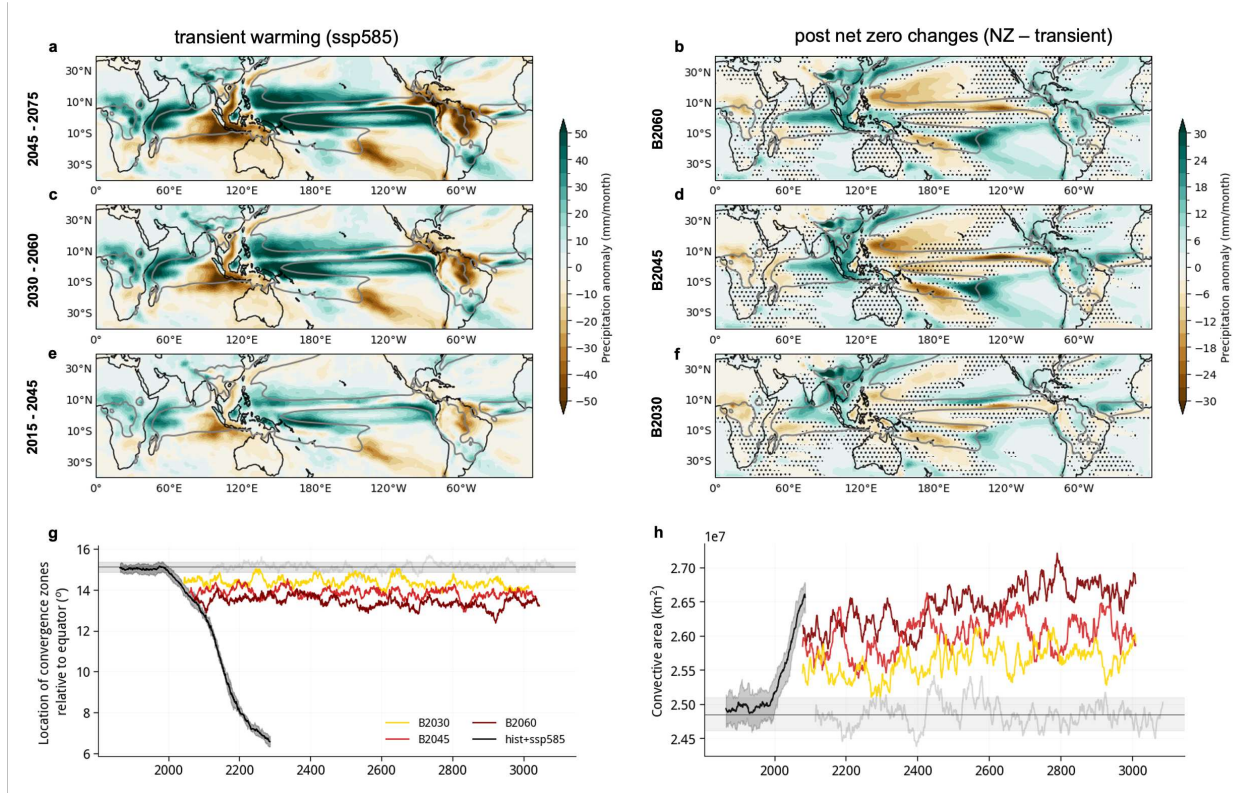


Figure 6. Persistent changes in tropical Pacific rainfall belts and convective area in ACCESS-ESM1-5 net-zero runs. **a, b,** Precipitation anomaly under transient warming, compared to historical, during 2045–2075 (**a**) and changes in precipitation anomaly post net-zero, compared to transient warming in the branching run B2060 compared to transient warming (**b**). The gray contour represents the 150 mm/month precipitation contour from the historical run during 1850–1900. **c, d** and **e, f** Same as **a, b** but for the transient warming period 2030–2060; net-zero B2045 and the transient warming period 2015–2045; net-zero B2030, respectively. Stippling represents the grid points where the post net-zero changes are statistically insignificant (see Methods). The changes post net-zero are calculated as the difference between net-zero and transient patterns. **g**, Evolution of the location of the convergence zones, ITCZ and SPCZ relative to the equator (see Methods), during historical and transient warming (black) and under net-zero branching runs: B2030 (gold), B2045 (red) and B2060 (maroon). **h**, Same as **g** but for changes in the mean convective area in the tropical Pacific rainfall belt. The gray line in **g** and **h** represents the relative location and mean convective area respectively, in the piControl experiment. The thin black line is the piControl average across time and model ensemble, while the grey shading represents the 10th–90th percentile range.

detect persistent rainfall changes over East Asia and Australia linked to an El Niño-like mean state and a northward-displaced SPCZ, although a more detailed hydroclimatic assessment is warranted for future studies. These findings are consistent with studies demonstrating that tropical and extratropical rainfall responses can be modulated by Southern Ocean warming [60, 61].

Consistent with the hemispheric asymmetric warming, Southern Hemisphere zonal trade wind stress weakens and remain suppressed after net-zero, while Northern Hemisphere zonal trade wind stress partially recovers (Fig.7a–f). We find that near-surface wind anomalies are dynamically coupled to basin-scale asymmetric sea level pressure changes (Supplementary Fig.8). The net effect is sustained weakening of the easterlies over the Niño3 region (Fig. 7g), which reinforces an El Niño-like background state. These circulation adjustments align with prior studies linking Southern Ocean heat uptake and interhemispheric gradient changes to tropical wind and SST changes [30, 62–64]. Previous studies have highlighted the importance of Southern Ocean heat uptake efficiency in strengthening the ZTG in slab ocean models [19, 27, 29, 65]. Watanabe et al.[14] hypothesised that this relationship could reverse in future warming scenarios, and our results corroborate this reversal under sustained deep-ocean heat storage.

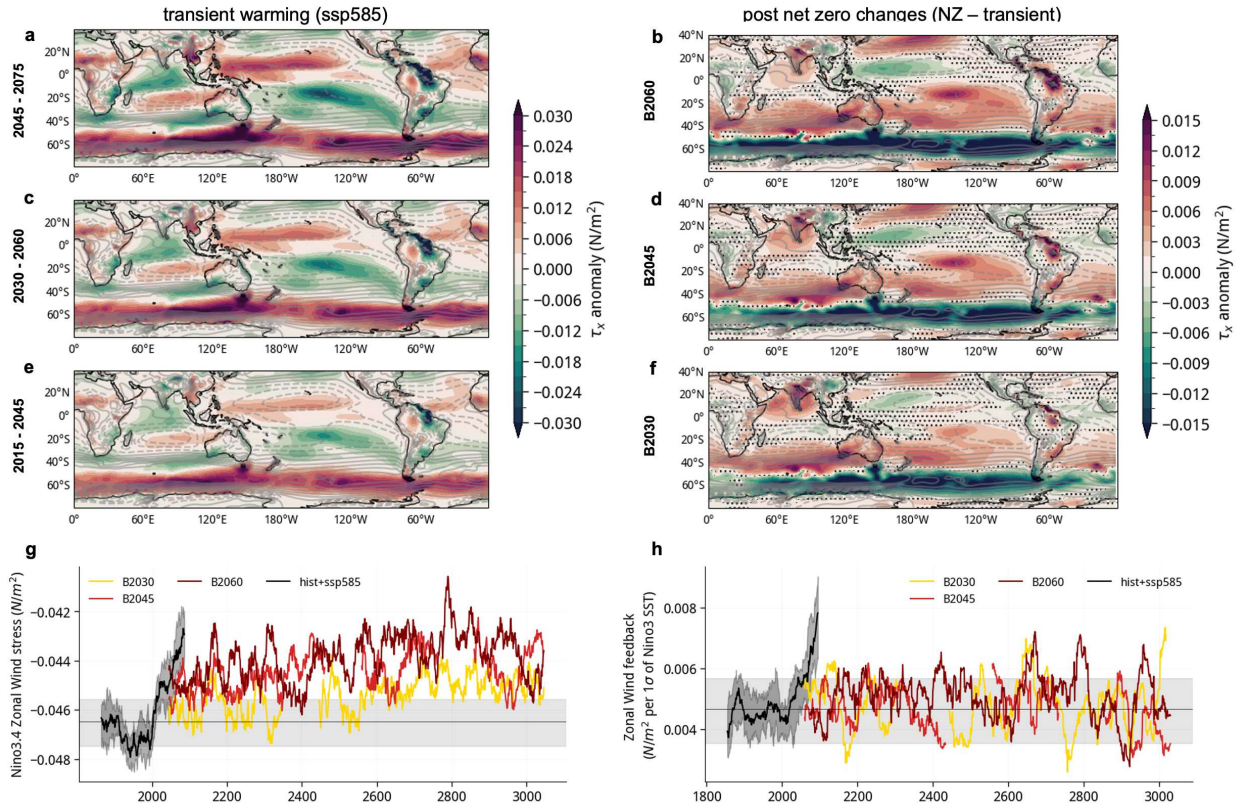


Figure 7. Changes in surface zonal wind stress and tropical Pacific zonal wind stress-SST feedback under transient warming and post net-zero in ACCESS-ESM1-5 net-zero runs. **a, b,** Surface zonal wind stress anomaly under transient warming, compared to historical, during 2045–2075 (**a**) and changes in zonal wind stress anomaly post net-zero in the branching run B2060 compared to transient warming (**b**). The solid (dashed) gray contours represent the positive (negative) values from the historical run during 1850–1900. **c, d** and **e, f** Same as **a, b** but for transient warming period 2030–2060; net-zero B2045 and transient warming period 2015–2045; net-zero B2030, respectively. Stippling represents those points where the post net-zero changes are statistically insignificant (see Methods). **g,** Evolution of zonal wind stress in the central Pacific (Niño3.4 region), during historical and transient warming (black) and under net-zero branching runs: B2030 (gold), B2045 (red) and B2060 (maroon). **h,** Same as **g** but for changes in the zonal wind stress-SST feedback in the Niño3 region (see Methods). The thin black line in panels **g** and **h** represents the 1850–1900 average, while the grey shading represents the 10th–90th percentile range.

During transient warming, rapid surface warming combined with slower deep-ocean equilibration flattens the 20°C isotherm (Z20) slope, through shoaling in the west and deepening in the east (Fig.8a,c,e,g). Post net-zero, the surface temperatures cool slightly, while the subsurface warms on slower timescales causing the Z20 slope to remain weakened (Fig.8b,d,f,g). We find hemispherically asymmetric changes in the Indo-Pacific shallow overturning Subtropical Cells (STCs; Supplementary Fig.9), consistent with the asymmetric changes in mid-latitude MSLP. Under transient warming, the subtropical ridge strengthens (weakens) over the Southern (Northern) Pacific Ocean (Supplementary Fig.8a,c,e) which drives Ekman pumping (suction) thereby enhancing (reducing) downwelling and strengthening (weakening) the Southern (Northern) Hemispheric STC (Supplementary Fig.9a,c,e). Post net-zero, anomalously low MSLP develops over the Southern Pacific Ocean with cyclonic winds (vectors in Supplementary Fig.8b,d,f) which drive anomalous Ekman suction and weaken the Southern Hemispheric STC, while the Northern Hemispheric STC recovers. The persistent slowdown of STCs reduces the upwelling of cold water, keeping the surface ocean warm, while the sustained subsurface warming keeps upwelled waters in the eastern Pacific relatively warm and inhibits recovery of ZTG. Even after radiative forcing stabilises, ocean thermal inertia maintains a weakened zonal gradient.

To understand how these structural shifts affect variability, we analysed wind and thermocline feedbacks

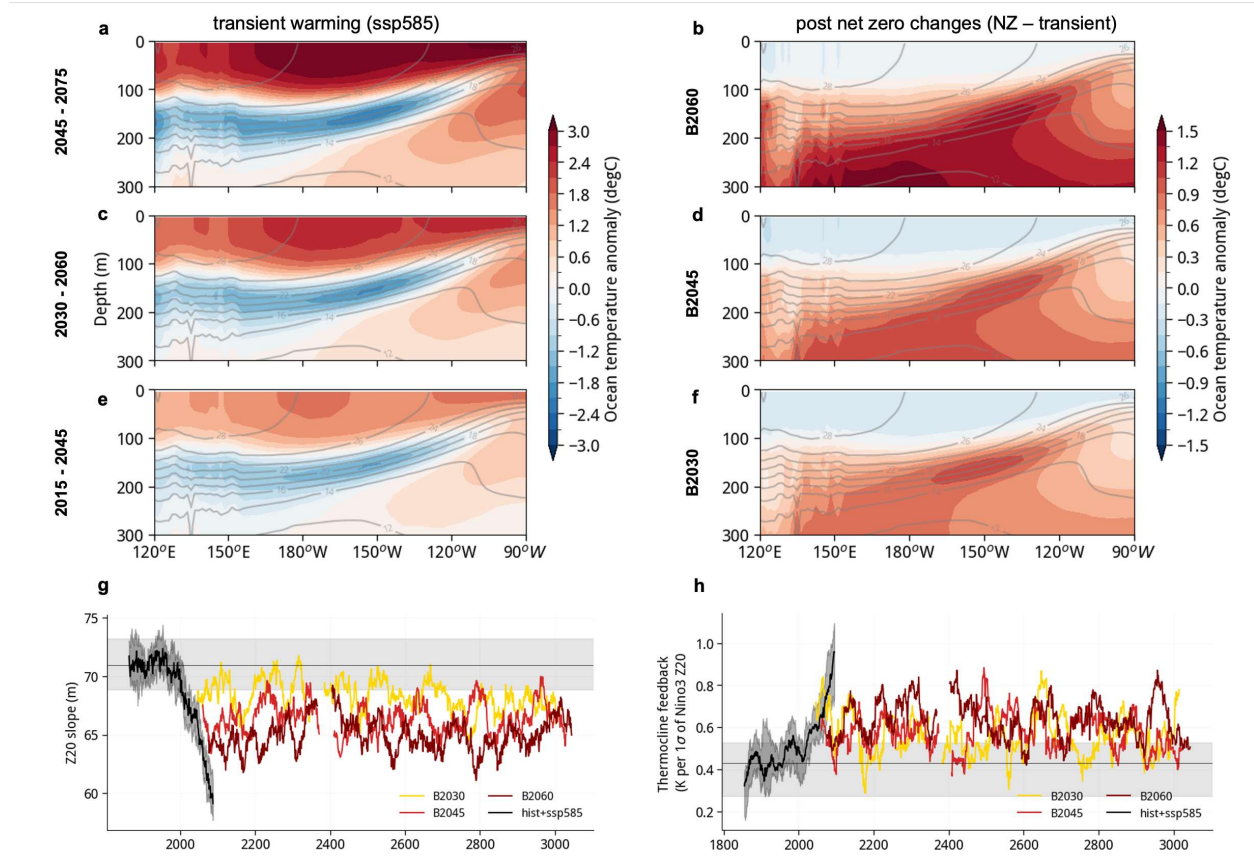


Figure 8. Long-term subsurface ocean temperature, thermocline slope and thermocline feedback changes in the equatorial Pacific in ACCESS-ESM1-5 net-zero runs. **a, b,** Tropical Pacific subsurface ocean potential temperature anomaly, averaged between 5°S and 5°N, under transient warming, compared to historical, during 2045–2075 (**a**) and changes in temperature anomaly post net-zero in the branching run B2060 compared to transient warming (**b**). The gray contours represent the temperature values from the historical run during 1850–1900. **c, d** and **e, f** Same as **a, b** but for transient warming period 2030–2060; net-zero B2045 and transient warming period 2015–2045; net-zero B2030, respectively. Stippling represents those points where the post net-zero changes are statistically insignificant (see Methods). **g,** Evolution of 20°C isotherm slope calculated as the gradient of the 20°C isotherm between the west and east equatorial Pacific (see Methods), during historical and transient warming (black) and under net-zero branching runs: B2030 (gold), B2045 (red) and B2060 (maroon). **h,** Same as **g** but for changes in the SST-thermocline feedback in the Niño3 region (see Methods). The thin black line in panels **g** and **h** represents the 1850–1900 average, while the grey shading represents the 10th–90th percentile range.

using a linear regression analysis (see Methods) across transient and stabilisation scenarios. During transient warming, the wind–SST feedback strengthens (Fig. 7h), indicating an enhanced atmospheric response to Pacific SST anomalies. However, this increase is not statistically significant after emission cessation even in the delayed branching run (B2060), with the changes being well within the range of values that occur in the 1850–1900 baseline (gray shading in Fig. 7h). This suggests that atmospheric coupling adjusts relatively quickly once the increase in radiative forcing ceases.

In contrast, oceanic feedbacks exhibit a more robust and persistent intensification on longer stabilisation timescales. The thermocline–SST feedback strengthens under greenhouse warming and remains elevated after net-zero (Fig. 8h), implying increased sensitivity of eastern Pacific SST anomalies to subsurface anomalies. Wind–thermocline coupling also intensifies and persists post net-zero: for a given wind stress anomaly, the zonal thermocline slope (west–east Z20 gradient) exhibits a larger response, reflected in a more negative regression coefficient (Supplementary Fig. 7d). This indicates more efficient dynamical tilting of the thermocline and a strengthened thermocline feedback on longer timescales. The weakening in thermocline tilt is

more pronounced in the delayed-cessation pathway (B2060) and weaker in earlier-branching scenarios such as B2030, highlighting again the importance of early mitigation.

Conclusion

Here, we have examined how tropical Pacific changes post net-zero can be very different from the transient climate we are accustomed to. Our results demonstrate that delayed emission cessation substantially increases the persistence of an El Niño-like mean state, elevated ENSO amplitude on centennial timescales and persistent changes in tropical convection patterns. Deep-ocean heat storage and hemispheric asymmetry can reorganise atmospheric–oceanic coupling in ways that persist for centuries. While atmospheric feedback changes are more pronounced on transient timescales, structural modifications of the upper ocean can persist for centuries. Wind anomalies more effectively tilt the thermocline, and thermocline anomalies more effectively generate SST anomalies. These changes, combined with a persistently weakened ZTG favour enhanced eastern Pacific convection [7, 15, 59], lead to amplified ENSO variability even after emissions cease [66]. Net-zero stabilisation thus represents a clear regime shift in ENSO dynamics, rather than a simple reversal of transient warming.

At the same time, we find clear benefits of early mitigation: earlier stabilisation pathways limit the magnitude and persistence of oceanic feedback strengthening, reducing the risk of long-lived regime shifts. Delaying net-zero markedly increases the frequency of extreme El Niño events—comparable to 1997/1998 or 2015/2016—over subsequent centuries. We use a single ESM large ensemble in our study, which helps us to assess confidence in the forced response versus internal variability [13, 40], but this does not provide any indication of model uncertainty. Model uncertainties in future changes of both tropical and extratropical processes could influence the extent of tropical Pacific changes post emission cessation. Longer net-zero simulations across multiple models are therefore needed to better understand and communicate systematic changes in post net-zero circulation [67, 68]. In addition, we only consider the impact of CO₂ emission cessation. Changes in other greenhouse gases (GHGs) and even non-GHG regional emissions, like aerosols, can also have an impact on the tropical Pacific climate [14, 25], which needs to be explored in future studies. Further research exploring the implications of these ENSO and mean state shifts on post net-zero weather and teleconnections is sorely needed for more informed decision-making aligned with the Paris Agreement.

Methods

ZECMIP Archive

The ZECMIP experimental protocol was designed to constrain the value of the zero emissions commitment (ZEC; see Supplementary Fig.5a), the global temperature change after CO₂ emission cessation [44, 69]. We used simulations from the tier-1 type A experiment branching off from the 1pctCO₂ experiment. In the 1pctCO₂ run, the climate warms with a prescribed atmospheric CO₂ increase of 1% per year for 140 years. There are three type A experiments, branching off after cumulative emissions of 750 PgC (brch-750PgC), 1000PgC (brch-1000PgC) and 2000PgC (brch-2000PgC), respectively. We used nine ESMs that submitted results using the brch-1000PgC simulation protocol: ACCESS-ESM1-5, CanESM5, CESM2, GFDL-ESM4, GISS-E2-1-G-CC, MIROC-ES2L, MPI-ESM1-2-LR, NorESM2-LM and UKESM1-0-LL. Out of these nine ESMs, only three models: ACCESS-ESM1-5, MIROC-ES2L and UKESM1-0-LL completed all three branching experiments.

At the branching point, the emissions are set to zero and the climate is allowed to evolve freely, with the interactive carbon cycle activated to allow carbon to be exchanged between the Earth system components. In these runs, only CO₂ emissions are set to zero and all other forcings, such as non-CO₂ GHGs and aerosols, remain at prescribed preindustrial levels. We used the piControl experiment of each of these models for comparing the changes under transient forcing and post emission cessation changes. The piControl experiment uses constant external forcing to isolate natural internal climate variability. All ZECMIP model experiments provided monthly temperature (*ts*) and precipitation (*pr*) outputs; however, we resampled the data to July-June averages as we were interested in analysing the changes on ENSO-event relevant time scales (multi-decadal to centennial).

Post emission cessation regional temperature changes in ZECMIP models under the brch-1000PgC experiment point to a clear north-south asymmetry [69] with the Southern Ocean warming and the Arctic and Northern Hemisphere cooling over both land and ocean as shown in the multimodel mean (MMM) change in Supplementary Fig.5b. But, there are some inter-model differences, as highlighted in Supplementary Fig.5c. Also, different changes are identified for the three models that ran the higher and lower branching runs. ACCESS-ESM1-5 and UKESM1-0-LL show a warming across all regions in the high branching run (brch-2000PgC), unlike MIROC-ES2L, which shows a more consistent warming pattern across different branching runs (Supplementary Fig.6). These differences across models could be due to their equilibrium climate sensitivity, but the shorter runs also mean that we cannot make statistically robust remarks about the inter-model uncertainties.

ACCESS-ESM1-5 1000-year long net-zero runs

ACCESS-ESM-1-5 is the Australian ESM that participated in the sixth phase of CMIP. Its configurations and basic model evaluation are outlined in the model description paper by Ziehn et al.[70]. The framework that motivates these long net-zero branching runs [40] is inherently different from that of the ZECMIP protocol. The net-zero runs were designed to analyse the implications of long-term climate stabilisation at different global warming levels, and consequently the implications of a delay in achieving net-zero CO₂ emissions. This provides a useful framework for policymakers to better understand the consequences of the Paris Agreement for the coming generations and beyond.

The net-zero runs are based on emissions-driven simulations with a fully interactive carbon cycle, branching from the *esm-ssp5-8.5* scenario at seven different years ranging from 2030 to 2060 in five-year intervals. At the branching points, CO₂ emissions were set to zero, while aerosols and non-CO₂ GHGs were set back to pre-industrial (1850) levels. Following the emission cessation, the climate was allowed to freely evolve for 1000 years. An overview of the global average, regional and systematic changes in the Earth system using these runs was carried out by King et al. [43].

In our study, we compare the net-zero branching runs with the piControl run and the 40-member concentration-driven large ensemble (SSP5-8.5) for a robust statistical comparison. Similar to the ZECMIP outputs, the ACCESS-ESM1-5 net-zero simulation outputs are available on a monthly frequency; but, we resampled the data to July-June averages. We use the following variables in this study: surface temperature (*ts*), precipitation (*pr*), ocean potential temperature (*thetao*; θ), ocean meridional stream function at depth (*msftmz*; ψ), mean sea level pressure (*psl*; MSLP) zonal and meridional winds at surface (*uas* and *vas*, respectively) and zonal wind stress (*tauu*; τ_x)).

As highlighted in previous studies [40, 43], these runs provide an idealised net-zero scenario with abrupt

emission cessation, but they present a useful framework for informing policymaking [34, 67].

ENSO characteristics

In this study, we investigate changes in three key ENSO characteristics: ENSO amplitude, ZTG and extreme El Niño events. For ENSO amplitude analysis, we first compute the Niño3 index in each of the runs as the detrended SST anomaly in the Niño3 region (5°S – 5°N ; 150°W – 90°W). The detrending is carried out by subtracting the 15-year rolling window average from the time series. Following this, the ENSO amplitude is calculated as the 30-year rolling standard deviation of the detrended Niño3 index. For robust multimodel comparison in the ZECMIP analysis, instead of using each models' ENSO amplitude, we compute the ENSO amplitude anomaly as the percentage change of ENSO amplitude compared to the piControl average in each individual model. This ensures that forced changes in ENSO amplitude in the models are not obfuscated by the model differences in the piControl baseline. For the time series and distributions plot, we use the median as the central tendency, and 10th–90th percentile range as the uncertainty/error bar range.

ZTG is calculated by first taking the difference in SST between west (5°S – 5°N ; 140°E – 170°E) and east equatorial Pacific (5°S – 5°N ; 170°W – 90°W) and then taking a 30-year rolling average to remove the influence of decadal-scale variability. Our results are not sensitive to the choice of the boxes for ZTG calculation, and are similar to the changes outlined in other studies using different regions [14, 15]. For the multimodel ZECMIP analysis, we use the ZTG anomaly (with respect to the piControl average), instead of ZTG to allow for a fair comparison across models as the mean state value of ZTG differs across models.

To distinguish between strong and extreme El Niño events, we follow the framework of Cai et al.[45], which links extreme events to changes in the meridional SST gradient (MTG) and associated rainfall shifts. MTG is calculated as the difference between SST anomalies in the Niño3 region from a region to its north (5°N – 10°N ; 150°W – 90°W). This metric captures the meridional temperature difference that drives southward shifts of the ITCZ during extreme events.

The years in which the Niño3 index time series exceeds one standard deviation of the piControl Niño3 index are classified as El Niño events in all runs. For strong events, we increase the threshold to 1.5 times the standard deviation of the piControl Niño3 index, and for extreme El Niño events we add another criterion of July-June average precipitation exceedance above 150 mm/month in the Niño3 region. Strong and extreme El Niño events thus correspond to those events that fall at the tail end of the MTG-precipitation relationship, indicative of a southward shift of the ITCZ along with enhanced temperature and rainfall variability in eastern equatorial Pacific. To enable comparison across simulations of different lengths, we express the events as a percentage of the total sample size. For the multimodel analysis, the sample size equals the total years in each model multiplied by the eight models used for this analysis (excluding GFDL-ESM4 model since *pr* variable was not available). In the single model large ensemble, the total sample size is determined by the number of years in the piControl and net-zero branching runs (i.e. $n = 999$). But, in the transient run, the sample size is the 30-years used for the analysis multiplied by 40, i.e. the number of ensemble members, (giving, $n = 1200$)

Spatial changes and statistical significance analysis

For spatial anomaly maps, we compute the changes under transient warming as anomalies compared to 1850–1900 historical baseline, shown by the grey contours. The transient warming anomalies are calculated in 30-year epochs centred at the year at which the net-zero branching occurs. The anomalies are then

306 averaged across the 40-member ensemble, except in Fig.5, where we only use a single ensemble member for
 307 the deep ocean anomalies due to computational and storage constraints. The regions chosen for the zonal
 308 and meridional cross-sections are adapted from Cai et al. [71]. The post net-zero changes are calculated as
 309 the difference between the average anomalies during the last 900 years (year 100 to 1000) in the net-zero
 310 branching runs and the 30-year baseline under transient warming centred at the year of branching.

311 To calculate the statistical significance of the changes post emission cessation, we create thirty random,
 312 non-overlapping 30-year pseudo ensembles using the net-zero branching runs from the last 900 years of each
 313 run. Then we compare the distribution of the pseudo-ensembles with the 40 ensemble member distribution in
 314 the SSP5-8.5 scenario using the non-parametric Mann-Whitney U test, at each grid point. Those grid points at
 315 which the two distributions are not found to be statistically different at the 95% confidence level are stippled.

316 **Location of Convergence zones, convective area and SST threshold for convection**

317 We choose the regions 0°–20°N, 130°E–80°W; and 20°S–0°, 130°E–140°W for calculating the location and
 318 displacement in tropical Pacific ITCZ and SPCZ, respectively, to avoid the double ITCZ bias in the southeast
 319 Pacific from obfuscating the analysis. Following the methodology outlined by Pontes et al. [52], we compute
 320 the ITCZ and SPCZ locations at each time step as the precipitation-weighted average over latitudes in which
 321 precipitation is greater than the maximum zonally averaged precipitation in each hemisphere. This captures
 322 the location of the ITCZ (D_{ITCZ}) and the SPCZ (D_{SPCZ}) independently. Then we compute the location of the
 323 convergence zones relative to the equator as

$$D_{net} = ||D_{ITCZ}| + |D_{SPCZ}|| \quad (1)$$

324 A decreasing trend in the value of D represents a net equatorward migration of both the convergence
 325 zones, while an increasing trend represents a net poleward migration.

326 We define the mean convective area in the tropical Pacific at any given time-step as the total area enclosed
 327 by the grid points within the region 20°S–20°N; 100°E–60°W, where the precipitation rate exceeds the
 328 threshold of 150 mm/month. The SST threshold for convection is defined as minimum SST in the same
 329 region, where the July-June average precipitation rate exceeds 150 mm/month.

330 **ENSO feedback analysis**

331 To quantify changes in ENSO dynamics under both transient warming and post-net-zero stabilisation, we
 332 diagnose key components of the Bjerknes feedback using linear regression analysis [72–75].

333 We first calculate the anomalies for all variables based on a tropical year(July–June), which are then
 334 detrended by subtracting a 15-year window rolling average from the time-series. For rolling diagnostics,
 335 we further subtract the mean within each window to isolate variability from residual low-frequency forcing.
 336 Regression slopes are computed using ordinary least squares temporal regression. To ensure robustness,
 337 regressions are calculated only when sufficient data coverage is available: windows with fewer than 70%
 338 valid (non-missing) values are excluded. This avoids artefacts arising from temporal gaps in the data.
 339 Extended periods of missing data are excluded from the analysis and do not contribute to regression
 340 estimates. To compare the data across both transient and stabilised climates with differing variance, regression

coefficients are expressed by multiplying the dimensional slope by the standard deviation of the independent variable within the same analysis window, yielding a response per one standard deviation of forcing. This approach follows established ENSO feedback analysis in both CMIP-class models and idealised frameworks [72, 74, 75].

Wind–SST (atmospheric) feedback The atmospheric feedback component of the Bjerknes feedback was quantified as the regression of zonal wind stress anomalies onto SST anomalies:

$$\tau'_x = \alpha T' \quad (2)$$

where T' denotes the eastern Pacific Niño3 SST anomalies and τ'_x represents the zonal wind stress anomalies averaged over the central Pacific Niño3.4 region (5°S–5°N; 170°W–120°W). The central Pacific is chosen to capture the region of strongest atmospheric coupling to SST anomalies and convective shifts during ENSO events [50, 74]. The resulting regression coefficient α represents the sensitivity of zonal wind stress to eastern Pacific SST anomalies and provides a measure of the atmospheric feedback strength.

Thermocline-SST (oceanic) feedback The oceanic vertical feedback was quantified by regressing Niño3 SST anomalies onto thermocline depth anomalies:

$$T' = \beta h' \quad (3)$$

where h' is the 20°C isotherm depth (Z20) anomaly averaged over the Niño3 region. The regression coefficient β represents the sensitivity of eastern Pacific SST anomalies to subsurface thermocline variations and reflects the strength of upwelling mediated coupling between subsurface heat content and surface temperature.

Wind-thermocline coupling The dynamical coupling between zonal wind stress and zonal thermocline tilt is diagnosed as:

$$\Delta h'_{W-E} = \gamma \tau'_x \quad (4)$$

where τ'_x is the zonal wind stress anomaly averaged over the Niño3.4 region, and $\Delta h'_{W-E}$ denotes the zonal thermocline slope anomaly, defined as the difference between western Pacific Z20 (5°S–5°N; 140°E–170°E) and eastern Pacific Z20 (5°S–5°N; 170°W–90°W) in the upper 300 meters. The west–east contrast captures the large-scale tilting of the equatorial thermocline associated with wind-driven Kelvin and Rossby wave adjustment [72, 74]. A more negative regression coefficient indicates stronger dynamical tilting for a given wind stress anomaly.

Data availability All simulations are available on the Australian node of the Earth System Grid Federation. The historical, piControl, 1pctCO2, ZECMIP tier 1 branching simulations, as well as ACCESS-ESM1-5 piControl, historical and SSP5-8.5 simulations are available here: <https://metagrid.esgf-west.org/search/cmip6>. The bespoke ACCESS net-zero runs will be made available once final revisions are made.

Code availability Analysis code required to reproduce the results of this study is available at https://github.com/adisen99/net_zeroenso_pacific_changes, archived on Zenodo at <https://doi.org/10.5281/zenodo.19336686> (ref.[76]).

Acknowledgments The PhD research of AS is supported by the University of Melbourne through the Melbourne Research Scholarship and John and Allan Gilmour Research Award (Science). AS, ADK, JRB, NM, MBF, EO, AST and SM also receive funding from the ARC Centre of Excellence for the Weather of the 21st Century (CE230100012). ADK, JRB and TZ receive funding from the Australian Government through the National Environmental Science Program (NESP). ADK also receive funding from an ARC Future Fellowship (FT240100306). NM receives funding from an ARC DECRA Fellowship (DE230100315). This research was undertaken with data supported by the Australian Government’s National Collaborative Research Infrastructure Strategy (NCRIS), with access to resources provided through the ACCESS-NRI Merit Allocation Scheme and the National Computational Infrastructure (NCI).

Author contributions AS, ADK and JRB. conceptualized the study. TZ carried out the experiments. AS performed the analysis and created the figures. NM, MBF, EO, AST, SM and AD provided feedback on the results. AS wrote the first draft and all authors contributed to writing and editing the manuscript.

Competing interests The authors declare no competing interests.

References

- [1] Liang, Y., Gillett, N. P. & Monahan, A. H. Accounting for Pacific climate variability increases projected global warming. *Nature Climate Change* **14**, 608–614 (2024). URL <https://www.nature.com/articles/s41558-024-02017-y>.
- [2] Alessi, M. J. & Rugenstein, M. A. A. Surface Temperature Pattern Scenarios Suggest Higher Warming Rates Than Current Projections. *Geophysical Research Letters* **50**, e2023GL105795 (2023). URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2023GL105795>. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1029/2023GL105795>.
- [3] Zhao, M. & Knutson, T. Crucial role of sea surface temperature warming patterns in near-term high-impact weather and climate projection. *npj Climate and Atmospheric Science* **7**, 1–13 (2024). URL <https://www.nature.com/articles/s41612-024-00681-7>.
- [4] Liu, Y., Cai, W., Lin, X., Li, Z. & Zhang, Y. Nonlinear El Niño impacts on the global economy under climate change. *Nature Communications* **14**, 5887 (2023). URL <https://www.nature.com/articles/s41467-023-41551-9>.
- [5] Cai, W. *et al.* Changing El Niño–Southern Oscillation in a warming climate. *Nature Reviews Earth & Environment* **2**, 628–644 (2021). URL <https://www.nature.com/articles/s43017-021-00199-z>.
- [6] Intergovernmental Panel On Climate Change (Ipcc). *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* 1 edn (Cambridge University Press, 2023). URL <https://www.cambridge.org/core/product/identifier/9781009157896/type/book>.
- [7] Cai, W. *et al.* Butterfly effect and a self-modulating El Niño response to global warming. *Nature* **585**, 68–73 (2020). URL <https://www.nature.com/articles/s41586-020-2641-x>.
- [8] Stuecker, M. F. *et al.* Global climate mode resonance due to rapidly intensifying El Niño–Southern Oscillation. *Nature Communications* **16**, 9013 (2025). URL <https://www.nature.com/articles/s41467-025-64619-0>.

- [9] Maher, N., Matei, D., Milinski, S. & Marotzke, J. ENSO Change in Climate Projections: Forced Response or Internal Variability? *Geophysical Research Letters* **45**, 11,390–11,398 (2018). URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2018GL079764>. eprint: <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2018GL079764>.
- [10] Wengel, C. *et al.* Future high-resolution El Niño/Southern Oscillation dynamics. *Nature Climate Change* **11**, 758–765 (2021). URL <https://www.nature.com/articles/s41558-021-01132-4>.
- [11] Callahan, C. W. *et al.* Robust decrease in El Niño/Southern Oscillation amplitude under long-term warming. *Nature Climate Change* **11**, 752–757 (2021). URL <https://www.nature.com/articles/s41558-021-01099-2>.
- [12] Zhu, Y. *et al.* Projection of ENSO using observation-informed deep learning. *Nature Communications* **16**, 7736 (2025). URL <https://pmc.ncbi.nlm.nih.gov/articles/PMC12365254/>.
- [13] Maher, N. *et al.* The future of the El Niño–Southern Oscillation: using large ensembles to illuminate time-varying responses and inter-model differences. *Earth System Dynamics* **14**, 413–431 (2023). URL <https://esd.copernicus.org/articles/14/413/2023/>.
- [14] Watanabe, M. *et al.* Possible shift in controls of the tropical Pacific surface warming pattern. *Nature* **630**, 315–324 (2024). URL <https://www.nature.com/articles/s41586-024-07452-7>.
- [15] Lee, S. *et al.* On the future zonal contrasts of equatorial Pacific climate: Perspectives from Observations, Simulations, and Theories. *npj Climate and Atmospheric Science* **5**, 1–15 (2022). URL <https://www.nature.com/articles/s41612-022-00301-2>.
- [16] Seager, R. *et al.* Strengthening tropical Pacific zonal sea surface temperature gradient consistent with rising greenhouse gases. *Nature Climate Change* **9**, 517–522 (2019). URL <https://www.nature.com/articles/s41558-019-0505-x>.
- [17] Heede, U. K. & Fedorov, A. V. Colder Eastern Equatorial Pacific and Stronger Walker Circulation in the Early 21st Century: Separating the Forced Response to Global Warming From Natural Variability. *Geophysical Research Letters* **50**, e2022GL101020 (2023). URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2022GL101020>. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1029/2022GL101020>.
- [18] Fu, S. *et al.* Historical changes in wind-driven ocean circulation drive pattern of Pacific warming. *Nature Communications* **15**, 1562 (2024). URL <https://www.nature.com/articles/s41467-024-45677-2>.
- [19] Kang, S. M. *et al.* Km-scale coupled simulation and model–observation sst trend discrepancy. *Proceedings of the National Academy of Sciences* **123**, e2522161123 (2026).
- [20] Jiang, F., Seager, R. & Cane, M. A. A climate change signal in the tropical Pacific emerges from decadal variability. *Nature Communications* **15**, 8291 (2024). URL <https://www.nature.com/articles/s41467-024-52731-6>.
- [21] Coats, S. & Karnauskas, K. B. Are Simulated and Observed Twentieth Century Tropical Pacific Sea Surface Temperature Trends Significant Relative to Internal Variability? *Geophysical Research Letters* **44**, 9928–9937 (2017). URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/2017GL074622>. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/2017GL074622>.
- [22] Latif, M. *et al.* Strengthening atmospheric circulation and trade winds slowed tropical Pacific surface warming. *Communications Earth & Environment* **4**, 1–10 (2023). URL <https://www.nature.com/articles/s43247-023-00912-4>.
- [23] Heede, U. K., Fedorov, A. V. & Burls, N. J. A stronger versus weaker Walker: understanding model differences in fast and slow tropical Pacific responses to global warming. *Climate Dynamics* **57**, 2505–2522 (2021). URL <https://doi.org/10.1007/s00382-021-05818-5>.
- [24] Hwang, Y.-T., Xie, S.-P., Chen, P.-J., Tseng, H.-Y. & Deser, C. Contribution of anthropogenic aerosols to persistent La Niña-like conditions in the early 21st century. *Proceedings of the National Academy of Sciences* **121**, e2315124121 (2024). URL <https://www.pnas.org/doi/10.1073/pnas.2315124121>.

- [25] Heede, U. K. & Fedorov, A. V. Eastern equatorial Pacific warming delayed by aerosols and thermostat response to CO₂ increase. *Nature Climate Change* **11**, 696–703 (2021). URL <https://www.nature.com/articles/s41558-021-01101-x>.
- [26] Chung, E.-S. *et al.* Tropical eastern Pacific cooling trend reinforced by human activity. *npj Climate and Atmospheric Science* **7**, 1–12 (2024). URL <https://www.nature.com/articles/s41612-024-00713-2>.
- [27] Kang, S. M. *et al.* Global impacts of recent Southern Ocean cooling. *Proceedings of the National Academy of Sciences* **120**, e2300881120 (2023). URL <https://www.pnas.org/doi/10.1073/pnas.2300881120>.
- [28] Kang, S. M., Ceppi, P., Yu, Y. & Kang, I.-S. Recent global climate feedback controlled by Southern Ocean cooling. *Nature Geoscience* **16**, 775–780 (2023). URL <https://www.nature.com/articles/s41561-023-01256-6>.
- [29] Kang, S. M., Shin, Y., Kim, H., Xie, S.-P. & Hu, S. Disentangling the mechanisms of equatorial Pacific climate change. *Science Advances* **9**, eadf5059 (2023). URL <https://www.science.org/doi/10.1126/sciadv.adf5059>.
- [30] Tseng, H.-Y. & Hwang, Y.-T. Contrasting the Evolution of the Tropical Pacific SST Responses to Time-Invariant Extratropical Forcings in the Two Hemispheres. *Geophysical Research Letters* **51**, e2024GL110551 (2024). URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2024GL110551>. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1029/2024GL110551>.
- [31] Fu, M. & Fedorov, A. The Role of Bjerknes and Shortwave Feedbacks in the Tropical Pacific SST Response to Global Warming. *Geophysical Research Letters* **50**, e2023GL105061 (2023). URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2023GL105061>. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1029/2023GL105061>.
- [32] Heede, U. K., Fedorov, A. V. & Burls, N. J. Time Scales and Mechanisms for the Tropical Pacific Response to Global Warming: A Tug of War between the Ocean Thermostat and Weaker Walker (2020). URL <https://journals.ametsoc.org/view/journals/clim/33/14/JCLI-D-19-0690.1.xml>.
- [33] McGregor, S., Ong, E. Q. & Planton, Y. Y. Understanding cmip6 multi-model ensemble projected pacific warming pattern variability. *Geophysical Research Letters* **53**, e2025GL118815 (2026).
- [34] King, A. D. *et al.* Preparing for a post-net-zero world. *Nature Climate Change* **12**, 775–777 (2022). URL <https://www.nature.com/articles/s41558-022-01446-x>.
- [35] Liu, C. *et al.* Hysteresis of the El Niño–Southern Oscillation to CO₂ forcing. *Science Advances* **9**, eadh8442 (2023). URL <https://www.science.org/doi/10.1126/sciadv.adh8442>.
- [36] Park, I.-H. *et al.* Irreversible changes in the sea surface temperature threshold for tropical convection to CO₂ forcing. *Communications Earth & Environment* **5**, 659 (2024). URL <https://www.nature.com/articles/s43247-024-01751-7>.
- [37] Wang, G. *et al.* Continued increase of extreme El Niño frequency long after 1.5 °C warming stabilization. *Nature Climate Change* **7**, 568–572 (2017). URL <https://www.nature.com/articles/nclimate3351>. Number: 8.
- [38] Schleussner, C.-F. *et al.* Overconfidence in climate overshoot. *Nature* **634**, 366–373 (2024). URL <https://www.nature.com/articles/s41586-024-08020-9>.
- [39] Gidden, M. J. *et al.* A prudent planetary limit for geologic carbon storage. *Nature* **645**, 124–132 (2025). URL <https://www.nature.com/articles/s41586-025-09423-y>.
- [40] King, A. D. *et al.* Studying climate stabilization at Paris Agreement levels. *Nature Climate Change* **11**, 1010–1013 (2021). URL <https://www.nature.com/articles/s41558-021-01225-0>.
- [41] Solomon, S., Plattner, G.-K., Knutti, R. & Friedlingstein, P. Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences* **106**, 1704–1709 (2009). URL <https://www.pnas.org/doi/10.1073/pnas.0812721106>.

- [42] Eby, M. *et al.* Lifetime of Anthropogenic Climate Change: Millennial Time Scales of Potential CO₂ and Surface Temperature Perturbations (2009). URL <https://journals.ametsoc.org/view/journals/clim/22/10/2008jcli2554.1.xml>.
- [43] King, A. D. *et al.* Exploring climate stabilisation at different global warming levels in ACCESS-ESM-1.5. *Earth System Dynamics* **15**, 1353–1383 (2024). URL <https://esd.copernicus.org/articles/15/1353/2024/>.
- [44] Jones, C. D. *et al.* The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) contribution to C4MIP: quantifying committed climate changes following zero carbon emissions. *Geoscientific Model Development* **12**, 4375–4385 (2019). URL <https://gmd.copernicus.org/articles/12/4375/2019/>.
- [45] Cai, W. *et al.* Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change* **4**, 111–116 (2014). URL <https://www.nature.com/articles/nclimate2100>.
- [46] Bayr, T., Lübbecke, J. F. & Fiedler, S. Is El Niño-Southern Oscillation a Tipping Element in the Climate System? *Geophysical Research Letters* **51**, e2023GL107848 (2024). URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2023GL107848>. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1029/2023GL107848>.
- [47] Liu, W., Li, S., Li, C., Rugenstein, M. & Thomas, A. P. Contrasting fast and slow intertropical convergence zone migrations linked to delayed Southern Ocean warming. *Nature Climate Change* **14**, 732–739 (2024). URL <https://www.nature.com/articles/s41558-024-02034-x>.
- [48] Peng, Q., Xie, S.-P. & Deser, C. Collapsed upwelling projected to weaken ENSO under sustained warming beyond the twenty-first century. *Nature Climate Change* **14**, 815–822 (2024). URL <https://www.nature.com/articles/s41558-024-02061-8>.
- [49] Geng, T., Cai, W., Jia, F. & Wu, L. Decreased ENSO post-2100 in response to formation of a permanent El Niño-like state under greenhouse warming. *Nature Communications* **15**, 5810 (2024). URL <https://www.nature.com/articles/s41467-024-50156-9>.
- [50] Cai, W. *et al.* ENSO and greenhouse warming. *Nature Climate Change* **5**, 849–859 (2015). URL <https://www.nature.com/articles/nclimate2743>.
- [51] Tuckman, P. J. Understanding ENSO Weakening in Warmer Climates. *Geophysical Research Letters* **52**, e2024GL113124 (2025). URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2024GL113124>. eprint: <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2024GL113124>.
- [52] Pontes, G. M., da Silva Dias, P. L. & Menviel, L. Rapid communication: Nonlinear sensitivity of the El Niño–Southern Oscillation across climate states. *Climate of the Past* **21**, 1079–1091 (2025). URL <https://cp.copernicus.org/articles/21/1079/2025/>.
- [53] Jiang, S. *et al.* The mean state of the tropical Pacific Ocean differed between the Medieval Warm Period and the Industrial Era. *Communications Earth & Environment* **4**, 1–9 (2023). URL <https://www.nature.com/articles/s43247-023-00734-4>.
- [54] Thirumalai, K. *et al.* Future increase in extreme El Niño supported by past glacial changes. *Nature* 1–7 (2024). URL <https://www.nature.com/articles/s41586-024-07984-y>.
- [55] Chung, E.-S. *et al.* Paleoclimate proxy records suggest reduced tropical Pacific zonal asymmetry under sustained global warming. *Communications Earth & Environment* **6**, 93 (2025). URL <https://www.nature.com/articles/s43247-025-02039-0>.
- [56] Pontes, G. M. *et al.* Mid-Pliocene El Niño/Southern Oscillation suppressed by Pacific intertropical convergence zone shift. *Nature Geoscience* **15**, 726–734 (2022). URL <https://www.nature.com/articles/s41561-022-00999-y>.
- [57] Kang, S. M., Shin, Y. & Xie, S.-P. Extratropical forcing and tropical rainfall distribution: energetics framework and ocean Ekman advection. *npj Climate and Atmospheric Science* **1**, 20172 (2018). URL <https://www.nature.com/articles/s41612-017-0004-6>.

- [58] Kang, S. M., Held, I. M., Frierson, D. M. W. & Zhao, M. The Response of the ITCZ to Extratropical Thermal Forcing: Idealized Slab-Ocean Experiments with a GCM (2008). URL <https://journals.ametsoc.org/view/journals/clim/21/14/2007jcli2146.1.xml>.
- [59] Kim, G.-I. *et al.* Deep ocean warming-induced El Niño changes. *Nature Communications* **15**, 6225 (2024). URL <https://www.nature.com/articles/s41467-024-50663-9>.
- [60] Jeong, H., Park, H.-S., Kang, S. M. & Chung, E.-S. The greater role of Southern Ocean warming compared to Arctic Ocean warming in shifting future tropical rainfall patterns. *Nature Communications* **16**, 2790 (2025). URL <https://www.nature.com/articles/s41467-025-57654-4>.
- [61] Kim, H. *et al.* Higher precipitation in East Asia and western United States expected with future Southern Ocean warming. *Nature Geoscience* 1–9 (2025). URL <https://www.nature.com/articles/s41561-025-01669-5>.
- [62] England, M. R., Polvani, L. M., Sun, L. & Deser, C. Tropical climate responses to projected Arctic and Antarctic sea-ice loss. *Nature Geoscience* **13**, 275–281 (2020). URL <https://www.nature.com/articles/s41561-020-0546-9>.
- [63] Zeller, M., McGregor, S. & Spence, P. Hemispheric Asymmetry of the Pacific Shallow Meridional Overturning Circulation. *Journal of Geophysical Research: Oceans* **124**, 5765–5786 (2019). URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2018JC014840>. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1029/2018JC014840>.
- [64] Wang, K., Deser, C., Sun, L. & Tomas, R. A. Fast Response of the Tropics to an Abrupt Loss of Arctic Sea Ice via Ocean Dynamics. *Geophysical Research Letters* **45**, 4264–4272 (2018). URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2018GL077325>. eprint: <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2018GL077325>.
- [65] Hwang, Y.-T., Xie, S.-P., Deser, C. & Kang, S. M. Connecting tropical climate change with Southern Ocean heat uptake. *Geophysical Research Letters* **44**, 9449–9457 (2017). URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/2017GL074972>. eprint: <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2017GL074972>.
- [66] Oh, J.-H. *et al.* Emergent climate change patterns originating from deep ocean warming in climate mitigation scenarios. *Nature Climate Change* **14**, 260–266 (2024). URL <https://www.nature.com/articles/s41558-024-01928-0>.
- [67] King, A. D. *et al.* Enhancing communication of climate changes under net zero emissions. *Communications Earth & Environment* **6**, 526 (2025). URL <https://www.nature.com/articles/s43247-025-02472-1>.
- [68] King, A. D., Abram, N. J., Alastrué de Asenjo, E. & Ziehn, T. ESD Ideas: Extended net zero simulations are critical for informed decision making. *Earth System Dynamics* **16**, 1605–1609 (2025). URL <https://esd.copernicus.org/articles/16/1605/2025/>.
- [69] MacDougall, A. H. *et al.* Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO₂. *Biogeosciences* **17**, 2987–3016 (2020). URL <https://bg.copernicus.org/articles/17/2987/2020/>.
- [70] Ziehn, T. *et al.* The Australian earth system model: Access-esm1. 5. *Journal of Southern Hemisphere Earth Systems Science* **70**, 193–214 (2020).
- [71] Cai, W. *et al.* Southern Ocean warming and its climatic impacts. *Science Bulletin* **68**, 946–960 (2023). URL <https://linkinghub.elsevier.com/retrieve/pii/S2095927323002268>.
- [72] Jin, F.-F. An Equatorial Ocean Recharge Paradigm for ENSO. Part I: Conceptual Model (1997). URL https://journals.ametsoc.org/view/journals/atsc/54/7/1520-0469_1997_054_0811_aeorpf_2.0.co_2.xml.
- [73] Kim, S. T. & Jin, F.-F. An ENSO stability analysis. Part I: results from a hybrid coupled model. *Climate Dynamics* **36**, 1593–1607 (2010). URL <https://link.springer.com/article/10.1007/s00382-010-0796-0>.
- [74] Kim, S. T., Cai, W., Jin, F.-F. & Yu, J.-Y. ENSO stability in coupled climate models and its association

595 with mean state. *Climate Dynamics* **42**, 3313–3321 (2013). URL [https://link.springer.com/article/10.](https://link.springer.com/article/10.1007/s00382-013-1833-6)
596 1007/s00382-013-1833-6.
597 [75] An, S.-I. & Bong, H. Inter-decadal change in El Niño-Southern Oscillation examined with Bjerknes
598 stability index analysis. *Climate Dynamics* **47**, 967–979 (2015). URL [https://link.springer.com/article/](https://link.springer.com/article/10.1007/s00382-015-2883-8)
599 10.1007/s00382-015-2883-8.
600 [76] Sengupta, A. adisen99/net_zeroenso_pacific_changes: Zenodo- ready init submission (2026). URL
601 <https://doi.org/10.5281/zenodo.19336686>.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [projectENSOZTGpostnetzerosupp.pdf](#)