



A seasonal threshold on El Niño amplitude set by the Pacific zonal temperature gradient

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Abstract

El Niño is the largest year-to-year fluctuation of Earth's climate, and its strongest events disrupt rainfall across much of the planet. Each event weakens the Pacific trade winds, which are maintained by the west–east sea-surface temperature (SST) contrast that El Niño itself erodes. Whether this relationship imposes an upper limit on event amplitude remains unknown. Across three SST reconstructions for 1950–2025, we find that the zonal SST contrast decreases by about 1°C per degree of Niño3.4 warming within each calendar month. Extrapolating this relationship to zero contrast gives a seasonal threshold ranging from +1.8°C in April to +4.3°C in November; no month since 1950 has exceeded its corresponding threshold. Relative to the tropical mean SST, the threshold has changed little since 1870, as strengthening of the climatological gradient and tropical warming nearly offset each other. In historical near-zero-gradient months, the ocean advective terms associated with the Bjerknes feedback reversed, although these cases occurred only during the decay season. Across 57 coupled climate models, a near-zero gradient during September–December is associated with a lower probability of further Niño3.4 growth: 29%,



31 compared with 62% when 1–2°C of gradient remains. In 2026, the gradient reached a record
32 September low while El Niño was still developing. We define prospective observational tests to
33 assess whether the event continues to grow as the gradient approaches zero, providing a direct test
34 of the proposed constraint.

35

36 **1. Introduction**

37 The El Niño–Southern Oscillation (ENSO) arises from coupled interactions between the
38 tropical Pacific Ocean and the atmosphere. Its growth depends on coupled feedbacks, while its
39 evolution and termination also reflect ocean heat redistribution and surface heat exchange
40 (Bjerknes, 1969; Jin, 1997; Meinen and McPhaden, 2000). Despite substantial progress in
41 understanding these processes, the factors limiting the amplitude of the strongest El Niño events
42 remain uncertain (Levine et al., 2016; Takahashi and Dewitte, 2016; Cai et al., 2015). In particular,
43 it is unclear whether the tropical Pacific mean state imposes an upper constraint on event
44 amplitude, distinct from the processes that determine the peak of an individual event.

45 One possible constraint is the west–east sea-surface-temperature (SST) gradient across the
46 equatorial Pacific. During El Niño development, warming in the central and eastern Pacific
47 weakens the trade winds, reducing upwelling and changing thermocline depth and ocean advection
48 in ways that favour further warming (Jin, 1997; Bjerknes, 1969; Clarke, 2010). This Bjerknes
49 feedback also weakens the zonal SST contrast associated with the atmospheric circulation. If the
50 gradient becomes sufficiently small, the conditions supporting continued growth may weaken.
51 However, a vanishing regional SST gradient would not necessarily eliminate all positive
52 feedbacks: atmospheric convection, thermocline adjustment, ocean advection and stored heat can
53 continue to influence eastern Pacific SST.

54 Other processes can affect the maximum amplitude of an event. Changes in cloud shading and
55 surface heat exchange may limit further warming once the eastern Pacific SST becomes high
56 enough to support deep convection (Ramanathan and Collins, 1991; Wallace, 1992). The
57 convective threshold, approximately 27.5 °C in the present climate, varies with tropical-mean SST
58 (Graham and Barnett, 1987; Williams et al., 2009; Johnson and Xie, 2010). Equatorial heat-content
59 discharge contributes to event termination (Jin, 1997; Meinen and McPhaden, 2000). Conversely,
60 the atmospheric response can become nonlinear as convection extends eastward, potentially
61 amplifying strong events (Takahashi and Dewitte, 2016; Cai et al., 2018).



62 The mean zonal gradient could influence both the growth rate of ENSO perturbations and the
63 temperature contrast reached during a strong event, but these effects need not be equivalent. A
64 weaker mean gradient can favour greater ENSO instability, depending on accompanying changes
65 in the coupled system (Cai et al., 2015; Heede and Fedorov, 2023). At the same time, a sufficiently
66 weak gradient might limit the contrast available to an individual event. Geng et al. (2024), for
67 example, find that the simulated El Niño amplitude declines after 2100 as a permanent El Niño-
68 like mean state develops. Although this result concerns a much warmer climate, it motivates asking
69 whether gradient depletion could constrain event growth under present-day conditions.

70 Palaeoclimate evidence cautions against assuming a simple relationship between the mean
71 zonal gradient and ENSO variability. At the Last Glacial Maximum, when the Walker circulation
72 was stronger and the warm pool more contracted, individual-foraminifera records indicate 30–40%
73 lower El Niño variability (Ford et al., 2015; Thirumalai et al., 2024). El Niño variability was also
74 damped during the early Pliocene, when the zonal gradient was substantially weaker than today
75 (White and Ravelo, 2020). These findings concern variability rather than maximum event
76 amplitude. They nevertheless underline the need to distinguish how the mean state affects ENSO
77 variability and growth from whether it constrains the strongest events.

78 Two developments make an observational test timely. The observed zonal gradient has
79 strengthened since about 1980, against almost all coupled models (Seager et al., 2019; Seager et
80 al., 2022; Wills et al., 2022; Planton et al., 2026), so projections that link a weakening gradient to
81 more frequent extreme El Niño events (Cai et al., 2014) describe a mean state that has not arrived.
82 And the 2026 event reached a record weekly Niño3.4 anomaly in late September, about two
83 months earlier in the calendar than the previous record. A consensus of 13 forecasting centres
84 placed the October–December mean near +3.7 °C, with a peak around December (WMO, 2026).

85 Here we investigate whether the equatorial Pacific zonal SST gradient defines a seasonal
86 threshold for El Niño amplitude, defined as the Niño3.4 anomaly at which the gradient fitted for a
87 given calendar month reaches zero. We first establish the seasonal dependence of this threshold
88 and examine how observed El Niño events evolved as the gradient approached zero. We then
89 compare the zonal gradient with other components of the coupled system and assess whether the
90 threshold has changed relative to the tropical mean since 1870. This distinction helps determine
91 whether the relationship represents a fixed-temperature limit or depends on the evolving tropical
92 Pacific mean state. Because historical near-zero-gradient cases occurred only during the usual



93 decay season, they cannot establish whether gradient depletion independently limits event growth.
 94 We therefore define prospective tests using the 2026 event to assess the proposed constraint during
 95 the growth season, and examine whether coupled climate models exhibit comparable thresholds.

96

97 **2 Data and methods**

98 **2.1 Datasets and indices**

99 The primary SST dataset is ERSSTv5 (Huang et al., 2017), using monthly data from January
 100 1950 to September 2026; the September 2026 values are preliminary. We repeat the main
 101 diagnostics with COBE-SST2 (Hirahara et al., 2014; Table S1) and HadISST1 (Rayner et al.,
 102 2003), which extends to July 2026 in the version used here (Table S13). ERSSTv5 also provides
 103 an extended record back to 1870 (Table S2). Reconstructed SST datasets tend to underestimate the
 104 largest anomalies. To assess how this affects the estimated threshold, we therefore repeat the
 105 analysis using satellite-era OISST v2 (Reynolds et al., 2002), which better captures these extremes.
 106 These SST products are not fully independent because they draw in part on overlapping in-situ
 107 observations.

108 Niño3.4 is the area-weighted mean SST over 5°S–5°N, 170°–120°W. The eastern Pacific Niño3
 109 index is the corresponding mean over 5°S–5°N, 150°–90°W, and the warm-pool index is the mean
 110 over 5°S–5°N, 130°–160°E. We define the zonal SST gradient as warm-pool minus Niño3 absolute
 111 SST. SST anomalies are calculated relative to 1991–2020. The relative Niño3.4 index is the
 112 conventional Niño3.4 anomaly minus the ocean-mean SST anomaly between 20°S and 20°N,
 113 without rescaling (L’Heureux et al., 2024). Weekly Niño-region anomalies since 1982 are obtained
 114 from the NOAA Climate Prediction Center and dated by the centre of each week. These weekly
 115 data describe the timing and spatial development of the 2026 event; monthly SST reconstructions
 116 are used to estimate the fitted relationships and conduct the prospective tests.

117 Warm water volume above the 20°C isotherm over 5°S–5°N, 120°E–80°W is obtained from
 118 NOAA PMEL (Meinen and McPhaden, 2000). We standardise its anomaly over 1980–2025 to
 119 provide an index of equatorial ocean recharge. Thermocline tilt is defined as the mean depth of the
 120 20°C isotherm west of 155°W minus that east of 155°W, calculated from the PMEL volumes for
 121 the two regions divided by their respective areas. Monthly surface zonal wind over 5°S–5°N,
 122 160°E–150°W is taken from the NCEP–NCAR reanalysis for 1950–2025 (Kalnay et al., 1996).
 123 We also calculate the eastern Pacific meridional SST gradient as the mean SST over 5°–10°N



124 minus that over 2.5°S – 2.5°N , with both regions spanning 150° – 90°W . This provides a comparison
 125 with the zonal gradient because the meridional contrast also weakens during extreme El Niño
 126 events (Cai et al., 2014). Ocean temperature, currents, vertical velocity and net surface heat flux
 127 used in the heat-budget analysis are monthly means from the NCEP Global Ocean Data
 128 Assimilation System (GODAS; Behringer and Xue, 2004), covering January 1980 to September
 129 2026.

130

131 **2.2 The zero-gradient threshold and event definitions**

132 The climatological zonal SST gradient has a strong seasonal cycle, ranging from 2.1°C in April
 133 to 4.6°C in November. Pooling all months in a single regression would confound this seasonal
 134 cycle with interannual variability. We therefore regress the zonal SST gradient on the Niño3.4
 135 anomaly, allowing a separate intercept for each calendar month while constraining the slope to be
 136 the same across months. As a sensitivity test, we repeat the analysis with separate regressions for
 137 each calendar month. The zero-gradient threshold is defined as the Niño3.4 anomaly at which the
 138 fitted gradient reaches zero. Where observed anomalies do not approach this crossing, the
 139 threshold is a statistical extrapolation; interpreting it as a physical constraint therefore requires
 140 independent evidence from events in which the observed gradient approaches zero. We repeat the
 141 analysis using the relative Niño3.4 index.

142 All regression coefficients are estimated using data through 2025, excluding the developing
 143 2026 event from the fitted relationships. We calculate thresholds for 1950–2025, for three
 144 subperiods (1950–1974, 1975–1999 and 2000–2025), and in moving 30-year windows.
 145 Uncertainty ranges are the 5th–95th percentiles of block-bootstrap estimates, using 36-month
 146 blocks and 2,000 resamples; 600 resamples are used for the moving-window analysis. Block
 147 resampling accounts for temporal dependence rather than treating individual months as
 148 independent. Different periods are resampled independently. To assess the influence of extreme
 149 events, we also fit each subperiod after excluding the years of the five largest ERSSTv5 events
 150 (Table S3). Sensitivity to regional definitions, individual events, regression method and period
 151 boundaries is reported in Tables S4–S6 and Figure S1.

152 An El Niño event is defined as at least five consecutive months with Niño3.4 anomalies of at
 153 least $+0.5^{\circ}\text{C}$ and a peak anomaly of at least $+1.0^{\circ}\text{C}$. This criterion identifies 14 events since 1950.
 154 For each event, we calculate the gradient residual at the month of peak Niño3.4: the observed



gradient minus the value predicted by the fitted relationship for that calendar month and Niño3.4 anomaly. A negative residual indicates that the event had a weaker zonal SST gradient at its peak than the fitted relationship would suggest for an event of the same amplitude in that month.

2.3 Heat budget of the near-zero gradient months

We calculate the temperature budget for the upper 50 m of the eastern equatorial Pacific (Niño3 region). The temperature tendency is expressed as the sum of zonal, meridional and vertical advection, net surface heat flux divided by $\rho c_p H$, and a residual, where ρ is seawater density, c_p is its specific heat capacity and $H=50$ m. Each advective term is calculated at every grid point and model level from monthly-mean fields, averaged over the five GODAS levels spanning 0–50 m, and then averaged over the Niño3 region. Horizontal velocities are interpolated from the model B-grid to tracer points, and vertical velocity is interpolated from layer interfaces to model levels. The residual accounts for processes not resolved by this calculation, including sub-monthly covariances, diffusion and the ocean data-assimilation increments. It is large in some decay months, when tropical instability waves resume. All anomalies are calculated relative to the 1980–2025 calendar-month climatology.

We further decompose the zonal and vertical advection terms into contributions from the climatological mean flow, anomalous flow and their nonlinear interaction. Two terms of particular interest are the zonal advective feedback, $-u'\partial\bar{T}/\partial x$, and the thermocline feedback, $-\bar{w}\partial T'/\partial z$, where overbars denote climatological means and primes denote anomalies.

Growth seasons are defined as July–November of the onset year. Near-zero gradient months are those in which the ERSSTv5 zonal SST gradient is below 0.3°C . For the composite in Fig. 5d, all months with Niño3.4 anomalies above $+1^\circ\text{C}$ are grouped into bins according to the zonal SST gradient. Error bars show the standard errors of the bin means (Table S16).

2.4 Why a linear relation and a zero crossing are plausible

In the recharge-oscillator framework (Jin, 1997; Burgers et al., 2005), the eastern Pacific temperature anomaly T evolves according to

$$dT/dt = (a - c) T + \gamma h,$$

where a represents the Bjerknes feedback, c is thermal damping, and h is the thermocline-depth anomaly. The Bjerknes feedback links SST anomalies to wind anomalies and the resulting ocean



186 response, including changes in zonal advection and upwelling. Both pathways depend on the
 187 background tropical Pacific state, including the zonal SST gradient.

188 As a simple hypothesis, we assume that the effective coupling weakens in proportion to the
 189 zonal gradient that remains:

$$190 \quad a = a_0 G/\bar{G},$$

191 where G is the instantaneous zonal SST gradient and $\bar{G}$ is its climatological value for that month.
 192 Observationally, the gradient decreases approximately linearly with Niño3.4 warming, such that
 193 $G = \bar{G} - \beta T$ with $\beta \approx 1$ (Fig. 1a). Under these assumptions, the temperature-dependent growth rate
 194 is $\lambda(T) = a_0 (1 - \beta T/\bar{G}) - c$. The growth rate reaches zero at $T^* = (\bar{G}/\beta)(1 - c/a_0)$. This zero-growth
 195 point lies below the zero-gradient threshold, $\bar{G}/\beta$, when damping is positive and the initial coupling
 196 exceeds damping. The formulation therefore suggests three testable implications.

197 First, the threshold should inherit the seasonal cycle of the climatological gradient, being lower
 198 in spring and higher in late autumn (Fig. 1b). Second, if damping arrests growth before the gradient
 199 reaches zero, event peaks should generally occur below the zero-gradient threshold. The positive
 200 gradient residuals of central Pacific events and the absence of historical threshold exceedances are
 201 consistent with this expectation, although they do not establish its cause. Third, the feedbacks
 202 associated with the zonal gradient should weaken as the gradient approaches zero. The heat-budget
 203 analysis of near-zero-gradient months tests whether the relevant advective contributions behave
 204 accordingly (Fig. 5).

205 This simplified formulation does not determine the evolution of the stored ocean heat
 206 represented by γh . That term can continue to warm the eastern Pacific even when local
 207 temperature-dependent growth has weakened. Whether this stored heat sustains further warming
 208 or a plateau after the gradient approaches zero is therefore an open question addressed by the
 209 prospective growth-arrest test.

210

211 **2.5 Coupled models**

212 We analyse monthly sea-surface temperature from the CMIP6 historical simulations available
 213 through the Pangeo cloud archive (Eyring et al., 2016). After excluding two models with
 214 unstructured grids, 57 models remain. We use one ensemble member per model (r1i1p1f1 where
 215 available), selecting the regridded field when available and otherwise using the native grid. For
 216 1950–2014, we calculate the SST gradients over the same regions used for the observations,



217 applying cosine-latitude area weights. Anomalies are calculated relative to each simulation's own
 218 1950–2014 climatology.

219 For each model, we fit the same regression used for the observations: the warm-pool-minus-
 220 Niño3 zonal SST gradient as a function of the Niño3.4 anomaly, with a separate intercept for each
 221 calendar month and a common slope. We record the fitted slope, within-month correlation, April
 222 and November zero-gradient thresholds, climatological gradient, maximum Niño3.4 anomaly, and
 223 number of months in which the anomaly exceeds the threshold for that calendar month (Table
 224 S17). ERSSTv5 is fitted over the same 65-year period for comparison.

225 We then apply the growth-arrest test in Table 1 to months with Niño3.4 anomalies above +1°C
 226 and a zonal SST gradient below 0.3°C. The test is evaluated using up to three ensemble members
 227 per model. We count the cases in which Niño3.4 increases in the following month and compare
 228 their frequency with that in months when the gradient is between 1°C and 2°C. As a sensitivity
 229 test, we repeat the analysis using a model-specific near-zero-gradient threshold, obtained by
 230 scaling 0.3°C by the ratio of the standard deviation of each model's gradient anomalies to that in
 231 ERSSTv5 (Table S18).

232 The growth-arrest test of Table 1 is applied to every model month with Niño3.4 above +1 °C
 233 and less than 0.3 °C of the model's own gradient, in up to three members per model, counting those
 234 followed by a rise in Niño3.4 and comparing with months with 1–2 °C of gradient left; a second
 235 criterion scales 0.3 °C by the ratio of each simulation's to ERSSTv5's standard deviation of
 236 gradient anomalies (Table S18).

237

238 **3 Results**

239 **3.1 A seasonally varying zero-gradient threshold**

240 For each calendar month, the equatorial Pacific zonal SST gradient decreases approximately
 241 linearly with increasing Niño3.4 anomaly (Figure 1a). In ERSSTv5, the common slope is −1.03°C
 242 per degree of Niño3.4, with a within-month correlation of −0.88 (−0.65 when the months are
 243 pooled). Across the 25-year periods examined since 1870, slopes range from −0.96 to −1.14 (Table
 244 S2). Most of the reduction reflects eastern Pacific warming, while warm-pool SST changes
 245 comparatively little.

246

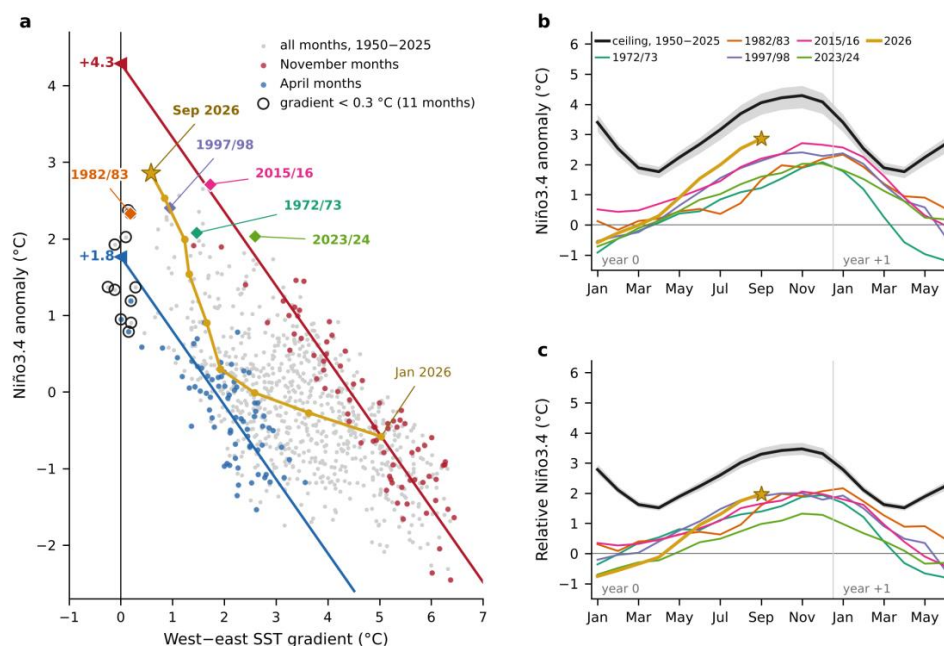


Figure 1. Seasonal relationships between Niño3.4 and the equatorial Pacific zonal SST gradient. (a) Relationship between the Niño3.4 anomaly and the west–east SST gradient, defined as warm-pool SST over 130°–160°E minus Niño3 SST, for January 1950–December 2025 in ERSSTv5. Anomalies are relative to 1991–2020. November and April observations are coloured, with fitted relationships using calendar-month intercepts and a common slope. Triangles identify the fitted zero-gradient thresholds. Circled observations are the 11 months with gradients below 0.3 °C. The five largest events are marked at their Niño3.4 peaks, and the 2026 trajectory extends from January to September; September is preliminary. (b) Calendar-month zero-gradient thresholds and their 5th–95th bootstrap percentile ranges, compared with Niño3.4 anomalies during the five largest events and 2026. (c) As in (b), using the relative Niño3.4 index, which subtracts the ocean-mean SST anomaly between 20°S and 20°N.

This relationship is partly influenced by the index definitions: Niño3 and Niño3.4 overlap spatially and covary strongly, whereas warm-pool SST responds comparatively weakly to Niño3.4. The near-unit negative slope is therefore not, by itself, evidence of a dynamical limit. The relevant question is whether El Niño can continue to grow as the observed gradient approaches zero. An eastern box at 120°–90°W that shares no grid cell with Niño3.4 gives a slope of -0.97 and a



265 November threshold of $+5.5^{\circ}\text{C}$, with no month above it (Table S5; Fig. S7). The relationship is
 266 not an artefact of the shared region, although the level of the threshold depends on the box.

267 The fitted zero-gradient threshold follows the seasonal cycle of the climatological gradient. It
 268 is lowest in April, at $+1.8^{\circ}\text{C}$, and highest in November, at $+4.3^{\circ}\text{C}$, with a November bootstrap
 269 range of $+3.9$ to $+4.6^{\circ}\text{C}$ (Figure 1b; Table S1). The other two SST datasets give closely comparable
 270 thresholds, within 0.1°C (Table S13). No monthly Niño3.4 anomaly during 1950–2025 exceeded
 271 its corresponding calendar-month threshold in any dataset or when the relative Niño3.4 index was
 272 used (Figure 1c). The closest approach was March 2016, at $+1.62^{\circ}\text{C}$ against a March threshold of
 273 $+1.89^{\circ}\text{C}$. Before 1950, when coverage was sparse, February 1878 reached the February threshold
 274 and exceeded it in relative units by 0.07°C (Table S2).

275 The threshold is more sensitive to the choice of regional SST indices than to the observational
 276 product. Alternative western or eastern Pacific boxes yield November thresholds of $+4.2$ to
 277 $+5.5^{\circ}\text{C}$, while changing the fitted slope by no more than 0.12 (Tables S4 and S5; Figure S1). The
 278 fitting method, the removal of any one of the five largest events, or a separate slope for each month
 279 move the November threshold by 0.55°C or less (Tables S4 and S5; Fig. S1).

280 The threshold also depends on the direction of regression. Regressing the gradient on Niño3.4
 281 estimates the expected gradient for a given anomaly; reversing the regression estimates the
 282 expected anomaly for a given gradient. The latter gives a November zero-gradient estimate of
 283 $+3.3^{\circ}\text{C}$, which was exceeded in three months since 1950 (Table S5). These estimates describe
 284 different conditional relationships and should not be treated as interchangeable bounds on El Niño
 285 amplitude. The forward regression provides the primary diagnostic, while the alternative quantifies
 286 its sensitivity to statistical assumptions.

287

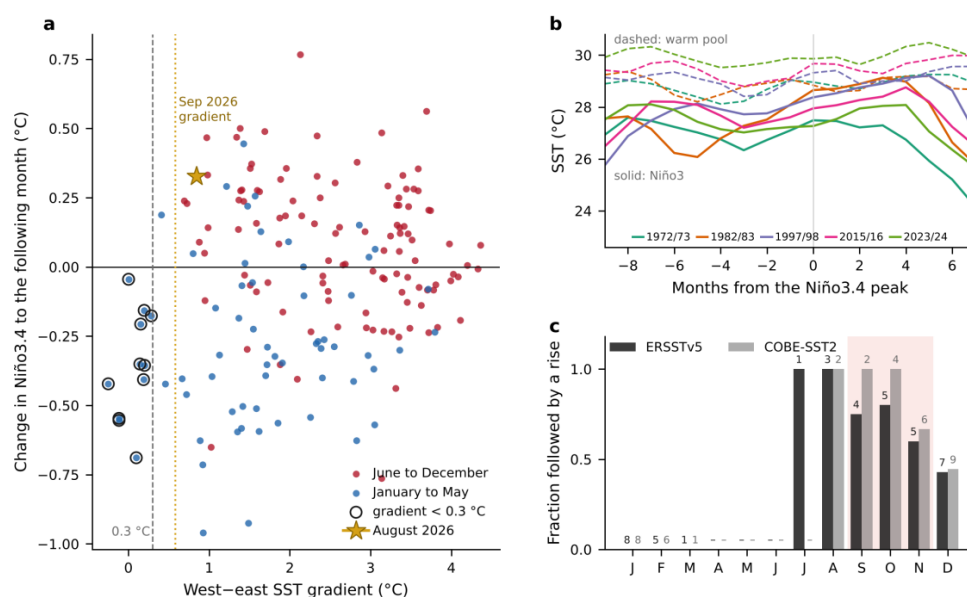
288 **3.2 What ran out when the gradient ran out**

289 Individual events differ in how much gradient they have left at their peak, and the difference
 290 depends on where they are centred. Eastern Pacific events cool the warm pool as they develop and
 291 approach zero gradient at lower Niño3.4 anomalies than central Pacific events. At their peaks, the
 292 eastern Pacific events of 1972/73, 1982/83 and 1997/98 had gradient residuals of -0.6 to -1.0°C ,
 293 whereas the central Pacific events of 2015/16 and 2023/24 had positive residuals (Table S7).

294 Across all 14 events, the gradient remaining at the peak decreases with eastward centring,
 295 measured as the Niño1+2 minus Niño4 anomaly at the month of peak Niño3.4. The gradient



296 remaining at the peak falls by 0.32°C per degree of this centring index ($r = -0.76$, $p = 0.002$; Figure
 297 S2; Table S8). Event structure therefore helps explain why a common fitted threshold does not
 298 necessarily coincide with the amplitude at which an individual event approaches zero gradient.
 299



300
 301 **Figure 2.** Observed near-zero gradients and subsequent El Niño evolution. (a) Change in Niño3.4
 302 anomaly to the following month as a function of the zonal SST gradient, for months with Niño3.4
 303 above $+0.5^{\circ}\text{C}$ during 1950–2025. January–May and June–December are distinguished. Circled
 304 observations identify the 11 ERSSTv5 months, belonging to three events, with gradients below
 305 0.3°C ; the dashed line marks this threshold. August 2026 is shown with its subsequent change to
 306 September. (b) Niño3 SST and contemporaneous warm-pool SST through the five largest events,
 307 aligned by the month of maximum Niño3.4 anomaly. Solid lines denote Niño3 and dashed lines
 308 the warm pool. (c) Fraction of months with Niño3.4 above $+1.5^{\circ}\text{C}$ followed by an increase, by
 309 calendar month, in ERSSTv5 and COBE-SST2; sample counts are shown.

310
 311 In ERSSTv5, 11 months had gradients below 0.3°C . These months belong to only three events,
 312 1982/83, 1991/92 and 1997/98, and all occurred at or after the respective Niño3.4 peaks. In every
 313 case, Niño3.4 decreased in the following month, by between 0.04 and 0.69°C (Figure 2a; Table
 314 S9). We adopt 0.3°C as an operational near-zero criterion because it is comparable to the



315 approximately 0.2 °C differences between SST reconstructions during strong events, so that a
 316 smaller gradient cannot reliably be distinguished from zero. Inter-product differences do not,
 317 however, capture all observational uncertainty.

318 The association persists when the near-zero threshold is varied between 0 and 0.4°C and is
 319 broadly reproduced in the other datasets. HadISST1 provides one exception, with a 0.02°C
 320 increase from April to May 1983 (Table S13). The result is therefore robust in its broad behaviour,
 321 but it is not an exception-free relationship across all products and thresholds.

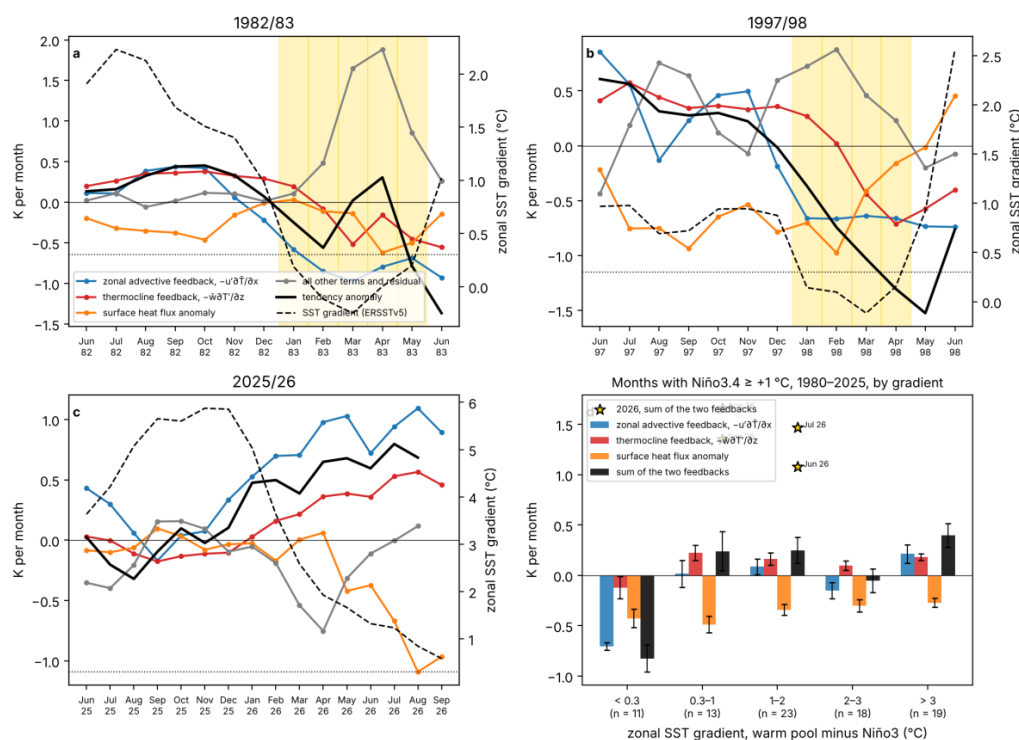
322 During the near-zero-gradient months, eastern Pacific SST approached contemporaneous
 323 warm-pool SST. Niño3 SST reached 29.1°C in April 1983 and 29.2°C in April 1998, within 0.2°C
 324 of the warm pool and three to five months after the Niño3.4 anomaly peaks (Figure 2b). By
 325 contrast, Niño3 SST in 2015/16 and 2023/24 remained 0.9°C and 2.3°C below the warm pool,
 326 respectively, at its maximum.

327 An ocean reanalysis shows how the heat budget changes as the zonal SST gradient approaches
 328 zero. We decompose the heat budget of the upper 50 m of the Niño3 region using NCEP GODAS
 329 (Behringer and Xue, 2004) and examine the two advective terms associated with the Bjerknes
 330 feedback (Sect. 2.3). One represents anomalous zonal flow acting on the mean zonal temperature
 331 gradient; the other represents mean upwelling acting on anomalous vertical temperature gradients.
 332 During the growth seasons of 1982, 1997 and 2015, these terms together contributed +0.6 to +0.8
 333 K month⁻¹ to the temperature tendency. In the near-zero-gradient months, their combined
 334 contribution reversed, reaching -1.0 K month⁻¹ in 1983 and -0.9 K month⁻¹ in 1998. Surface heat
 335 fluxes and the remaining budget terms kept the net layer tendency close to zero or negative (Fig.
 336 5a,b; Table S16).

337 The composite analysis supports this contrast. Across months since 1980 with Niño3.4
 338 anomalies above +1°C, the two terms sum to +0.25 K month⁻¹ when 1–2°C of zonal SST gradient
 339 remains, but to -0.83 ± 0.13 K month⁻¹ when the gradient falls below 0.3°C (Fig. 5d). The zonal
 340 advective term accounts for most of this reversal. Consistent with this change, the zonal
 341 temperature gradient within the Niño3 layer weakens from -0.4 to -0.6 K per 1,000 km during the
 342 growth seasons to -0.1 K per 1,000 km in the near-zero-gradient months. This weakening is
 343 consistent with a reduced temperature contrast available to drive anomalous zonal advection. The
 344 budget characterises the near-zero-gradient state, however; it cannot establish whether the gradient
 345 itself, rather than the seasonal evolution of the events, causes the reversal.



346



347

348 **Figure 3.** Heat budget of the Niño3 0–50 m layer through two exhausted events and the 2026 event
 349 (NCEP GODAS). (a–c) Monthly anomalies of the zonal advective feedback ($-u'\partial\bar{T}/\partial x$), the
 350 thermocline feedback ($-\bar{w}\partial T'/\partial z$), the net surface heat flux and all other terms including the
 351 residual, with the tendency anomaly (black) and the ERSSTv5 zonal SST gradient (dashed, right
 352 axis), for 1982/83, 1997/98 and 2025/26 to September 2026. Shading marks months with gradient
 353 below 0.3 °C (dotted line). (d) Means of the same terms, and of the sum of the two feedbacks, over
 354 all months with Niño3.4 above +1 °C from 1980 to 2025, binned by gradient, with standard errors;
 355 stars are the 2026 monthly sums.

356

357 These observations are consistent with gradient depletion limiting further El Niño growth, but
 358 they do not establish causation. All 11 near-zero-gradient months occurred between January and
 359 May, when strong events typically decay. None of the 14 January–May months with Niño3.4
 360 above +1.5°C was followed by an increase, compared with 10 of 14 September–November months



361 (Figure 2c; Table S13). The closest historical growth-season case was August 1997, when the
 362 gradient fell to 0.69°C but the event continued to grow.

363 The seasonal contrast is central to interpreting these results. The fitted threshold is only $+1.8$ to
 364 $+3.4^{\circ}\text{C}$ during January–May, compared with more than $+4^{\circ}\text{C}$ during September–December.
 365 Historical near-zero gradients therefore occurred when both the threshold and the event's seasonal
 366 tendency favour weakening. The observations do not distinguish a gradient-imposed constraint
 367 from the normal seasonal evolution of strong El Niño events.

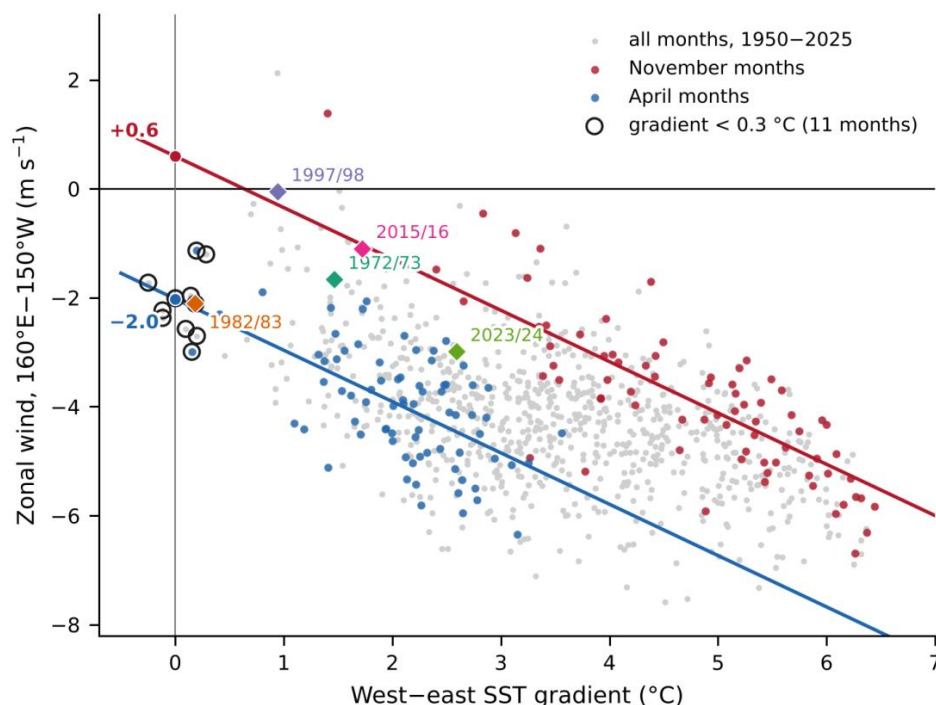
368

369 **3.3 Meridional gradient, thermocline tilt and surface wind**

370 Other components of the coupled system weaken alongside the zonal SST gradient, but their
 371 relationships with Niño3.4 do not identify a single common threshold. The eastern Pacific
 372 meridional SST gradient decreases by 0.58°C per degree of Niño3.4 warming, with a within-month
 373 correlation of -0.78 . Its fitted November zero crossing is $+4.8^{\circ}\text{C}$, approximately 0.5°C above the
 374 zonal gradient threshold (Table S10). The meridional gradient had reversed by the peak of the
 375 1982/83 event and remained positive at 0.8°C in September 2026.

376 Thermocline tilt decreases by approximately 20 m per degree of Niño3.4 warming from a
 377 climatological value of 82 m ($r=-0.88$; Table S11 and Figure S3). Its fitted November zero crossing
 378 is $+3.7^{\circ}\text{C}$, 0.4°C below the zonal SST gradient threshold estimated over the same 1980–2025
 379 period. Only the 1997/98 event exhibited a reversal of thermocline tilt. In August 2026, 26 m of
 380 tilt remained.

381 The relationship between zonal wind and the SST gradient also varies seasonally. Over 160°E –
 382 150°W , the regressed wind changes by -0.9 m s^{-1} per degree of zonal SST gradient ($r=-0.76$),
 383 indicating weaker easterlies as the gradient decreases. At zero fitted gradient, the wind is within
 384 0.6 m s^{-1} of zero during October–December (Figure S7). During January–May, however, the wind
 385 remains easterly at $1\text{--}2.4\text{ m s}^{-1}$. Winds were easterly during all 11 observed near-zero-gradient
 386 months, and only three months since 1950 had a westerly monthly mean, with each retaining 0.9--
 387 1.5°C of zonal gradient. The two other reanalyses agree (Table S15).



388

389 **Figure 4.** Surface zonal wind and the zonal SST gradient. Monthly NCEP–NCAR surface zonal
 390 wind over 5°S–5°N, 160°E–150°W (positive eastward) against the west–east SST gradient
 391 (ERSSTv5), January 1950 to December 2025. November and April months are coloured, with their
 392 lines from the fit of the wind on the gradient (calendar-month intercepts, common slope); the wind
 393 at zero gradient is marked. Circles are the 11 months with gradients below 0.3 °C, and the five
 394 largest events are marked at their peaks.

395 Together, these diagnostics show that the zonal SST gradient evolves in concert with changes in
 396 other components of the coupled system, but they do not identify a common threshold at which
 397 the system's feedbacks cease. In particular, a vanishing regional SST gradient does not imply that
 398 the trade winds or other positive feedbacks have shut down. The seasonal differences further
 399 motivate testing the proposed constraint during autumn, rather than during the established decay
 400 season.

401

402

403



404 **3.4 Conventional and tropical-relative thresholds**

405 The fitted threshold increased when expressed as a conventional Niño3.4 anomaly. In
 406 ERSSTv5, it rose from +4.05°C in 1950–1974 to +4.71°C in 2000–2025, an increase of
 407 approximately 0.7°C (bootstrap range: +0.17 to +1.16°C). The other datasets show larger increases
 408 (Tables S3 and S13). Estimates from moving 30-year windows were lowest, near +3.8°C, in
 409 windows centred on 1985 and 1993, and increased thereafter (Figure 3a).

410 The increase remains when the years of the strongest events are excluded. Its magnitude
 411 nevertheless depends on the choice of the period boundary, ranging from approximately +0.3°C
 412 for a split at 1990 to +0.8°C for a split at 2000 (Table S6). This sensitivity reflects the relatively
 413 low threshold during 1975–1999.

414 Much of the increase is attributable to background tropical warming relative to a fixed reference
 415 climatology. Ocean-mean SST between 20°S and 20°N increased by 0.58°C between the first and
 416 last periods. Such warming raises the conventional Niño3.4 anomaly without necessarily changing
 417 the west–east SST gradient.

418 When expressed relative to tropical-mean SST, the ERSSTv5 November threshold changes
 419 little, from +3.59°C in 1950–1974 to +3.57°C in 2000–2025. The bootstrap range for the change
 420 is –0.21 to +0.52°C (Figure S4). COBE-SST2 and HadISST1 retain smaller increases of
 421 approximately 0.3–0.4°C (Table S13). Across all 25-year periods examined since 1870, the
 422 ERSSTv5 relative threshold remains between +3.3 and +3.8°C (Table S2).

423 The small change reflects two nearly offsetting shifts in the mean state. The mean zonal gradient
 424 strengthened by 0.32°C between the first and last periods, implying that greater warming in the
 425 eastern Pacific was required to eliminate it. At the same time, the mean Niño3.4 temperature lay
 426 0.26°C further below the tropical mean. The stronger gradient therefore increased the separation
 427 between eastern and warm-pool SST without appreciably shifting the fitted tropical-relative
 428 threshold (Figure 3b).

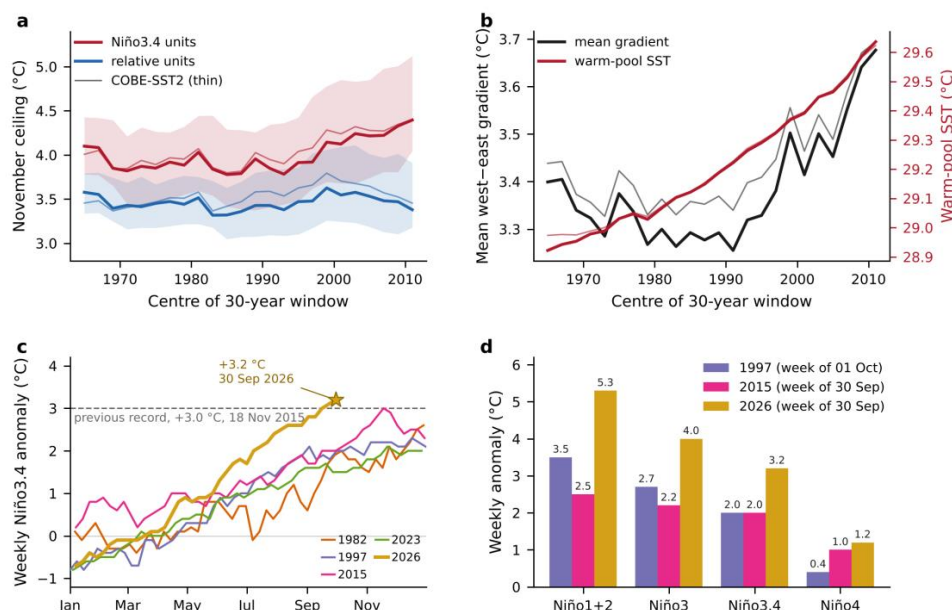


Figure 5. Changes in the fitted threshold and the development of the 2026 event. (a) November zero-gradient thresholds estimated in 30-year windows centred every two years from 1965 to 2011, using conventional and relative Niño3.4 anomalies. ERSSTv5 estimates include 5th–95th bootstrap percentile ranges; thin lines show COBE-SST2. (b) Mean zonal gradient and warm-pool SST in the same windows. (c) Weekly Niño3.4 anomalies through the calendar year for 1982, 1997, 2015, 2023 and 2026, ending with the week centred on 30 September 2026 (NOAA CPC). The dashed line marks the previous weekly record of +3.0 °C on 18 November 2015. (d) Weekly Niño1+2, Niño3, Niño3.4 and Niño4 anomalies for weeks centred on 1 October 1997, 30 September 2015 and 30 September 2026.

3.5 The 2026 event and the prospective tests

The 2026 event provides an opportunity to test the proposed constraint during a season when an already strong El Niño event can still intensify. The observed zonal SST gradient fell from 5.0°C in January to 0.58°C in September, moving from above to below the fitted relationship for the corresponding calendar months (Figure 1a). No earlier September in ERSSTv5 had such a small gradient; the previous minimum was 0.72°C in 1997. The preliminary September Niño3.4 anomaly of +2.86°C was the largest monthly value in the record, while the weekly anomaly



447 reached $+3.2^{\circ}\text{C}$ at the end of September, more than 1°C above the corresponding week in 1997
 448 and 2015 (Figure 3c).

449 The event is strongly eastern Pacific-centred. In September, Niño1+2 exceeded Niño4 by 3.2°C ,
 450 a difference exceeded at the peak of only the 1997/98 event. Warm-pool SST was slightly below
 451 normal (Figure 3d; Table S7). The zonal gradient was 0.65°C below the September fitted
 452 relationship, consistent with the historical association between eastward centring and negative
 453 gradient residuals.

454 Two further features distinguish the event. Tropical-mean SST reached a record anomaly of
 455 $+0.88^{\circ}\text{C}$, leaving the relative Niño3.4 anomaly at approximately $+2.0^{\circ}\text{C}$, below the peaks of
 456 1982/83, 1997/98 and 2015/16. Equatorial ocean recharge was also the largest in the 46-year
 457 record, reaching $+2.4$ standard deviations in August, compared with $+2.2$ before the 1997/98 event
 458 (Table S7). In July–September 2026, the two Bjerknes-related advective terms in the Niño3 heat
 459 budget summed to $+1.5 \text{ K month}^{-1}$, the largest three-month mean in the GODAS record (previous
 460 maximum $+1.1 \text{ K month}^{-1}$, in 1997). This positive contribution opposed a surface heat-flux
 461 anomaly of $-0.9 \text{ K month}^{-1}$, the most negative on record (Fig. 5c). The zonal temperature gradient
 462 within the Niño3 layer remained at $-0.5 \text{ K per } 1,000 \text{ km}$, well above the near-zero values found in
 463 the exhausted months.

464 We define two prospective tests, using thresholds calibrated on 1950–2025 (Table S12). The
 465 tests address different aspects of the proposed constraint.

466 The *growth-arrest test* asks whether Niño3.4 continues to rise after the observed zonal gradient
 467 becomes near zero. The hypothesis would be contradicted if the ERSSTv5 gradient fell below
 468 0.3°C in any month from October 2026 to March 2027 and Niño3.4 increased in the following
 469 month. Full evaluation therefore requires observations through April 2027. A decline following a
 470 near-zero gradient would be most informative in October or November: 7 of the 10 historical
 471 months in these two calendar months with Niño3.4 above $+1.5^{\circ}\text{C}$ were followed by growth. The
 472 corresponding proportion was 3 of 7 in December and zero from January to May.

473 The *amplitude test* asks whether the tropical-relative Niño3.4 anomaly exceeds a prospectively
 474 specified threshold derived from the fitted zero crossing. The decision thresholds are the 95th
 475 bootstrap percentiles: $+3.64^{\circ}\text{C}$ in October, $+3.68^{\circ}\text{C}$ in November, $+3.50^{\circ}\text{C}$ in December and
 476 $+2.96^{\circ}\text{C}$ in January. These percentiles quantify uncertainty in the fitted zero crossing; they are not



477 prediction limits for individual events. At a tropical-mean anomaly of $+0.88^{\circ}\text{C}$, the November
 478 threshold would correspond to a conventional Niño3.4 anomaly of approximately $+4.6^{\circ}\text{C}$.

479 The tests are complementary. Continued growth after the observed gradient becomes near zero
 480 would contradict the growth arrest hypothesis, even if the amplitude threshold were not exceeded.
 481 Conversely, an event could exceed the amplitude threshold while retaining a positive gradient, for
 482 example because its spatial structure differs from the fitted relationship. If the gradient remains
 483 above 0.3°C and the relative Niño3.4 anomaly remains below the specified thresholds, neither
 484 proposed constraint will have been challenged.

485 If the September gradient residual persists, the observed gradient would fall below 0.3°C at
 486 Niño3.4 anomalies of approximately $+3.3^{\circ}\text{C}$ in October and $+3.4^{\circ}\text{C}$ in November; the
 487 corresponding November estimate in COBE-SST2 is $+3.0^{\circ}\text{C}$. The consensus forecast places the
 488 October–December mean near $+3.7^{\circ}\text{C}$, with a peak around December. If the forecast amplitude
 489 and timing are realised and the negative gradient residual persists, the event could continue
 490 growing after reaching the near-zero criterion, contradicting the growth-arrest hypothesis.
 491 Alternatively, stored ocean heat could sustain a plateau, which would not by itself contradict the
 492 hypothesis defined here.

493

494 **Table 1.** Prospective tests of the proposed constraint against the 2026 event, fixed before the
 495 outcome (thresholds calibrated on ERSSTv5, 1950–2025).

Month	Growth-arrest test: gradient below ($^{\circ}\text{C}$)	Historical months above $+1.5^{\circ}\text{C}$ followed by a rise	Amplitude test: relative anomaly above ($^{\circ}\text{C}$)	Equivalent Niño3.4 anomaly at a tropical- mean anomaly of $+0.88^{\circ}\text{C}$ ($^{\circ}\text{C}$)
October 2026	0.3	7 of 10 (October and November)	$+3.64$	$+4.5$
November 2026	0.3		$+3.68$	$+4.6$
December 2026	0.3	3 of 7	$+3.50$	$+4.4$
January 2027	0.3	0 of 14 (January to May)	$+2.96$	$+3.8$
February 2027	0.3		$+2.24$	$+3.1$
March 2027	0.3		$+1.73$	$+2.6$

496

497

498



499 3.6 The threshold in coupled models

500 We apply the observational regression to monthly sea-surface temperature from 57 CMIP6
 501 models (Eyring et al., 2016) in the Pangeo cloud archive, using one ensemble member per model
 502 for 1950–2014. Anomalies are calculated relative to each model’s own climatology over this
 503 period, and ERSSTv5 is fitted over the same years. The fitted slopes range from -1.14 to -0.49°C
 504 per $^{\circ}\text{C}$ of Niño3.4 warming (median -0.87 ; ERSSTv5 -1.05), with 34 models within 0.2 of the
 505 observed slope. Within-month correlations range from -0.96 to -0.61 (median -0.88 ; ERSSTv5
 506 -0.90).

507 The November zero-gradient threshold ranges from $+1.76$ to $+10.13^{\circ}\text{C}$ across models, with a
 508 median of $+5.05^{\circ}\text{C}$, compared with $+4.37^{\circ}\text{C}$ in ERSSTv5. This spread reflects differences in both
 509 the climatological November gradient, which ranges from 1.98 to 5.93°C , and the fitted slope.
 510 Across models, the threshold correlates with the climatological gradient at 0.72 and with the signed
 511 regression slope at 0.83 . Figure 6 shows the relationship between the threshold and the
 512 climatological gradient. The median April threshold is $+2.88^{\circ}\text{C}$.

513 Twelve models (CESM2-FV2, CNRM-CM6-1, CNRM-ESM2-1, E3SM-1-0, EC-Earth3-Veg,
 514 FGOALS-f3-L, GISS-E2-1-G-CC, GISS-E2-1-G, GISS-E2-1-H, HadGEM3-GC31-MM, IITM-
 515 ESM and MIROC-ES2L) contain at least one month in which Niño3.4 exceeds the fitted threshold
 516 for that calendar month, accounting for 259 months in total. Yet the largest Niño3.4 anomaly
 517 reaches only $+2.9^{\circ}\text{C}$ in the median model, and exceeds $+3^{\circ}\text{C}$ in 24 models. The threshold is
 518 therefore not a common temperature limit across models. Rather, it depends on the climatological
 519 gradient and the rate at which that gradient decreases with Niño3.4 warming. Models with weaker
 520 climatological gradients tend to have lower thresholds, while biases in the mean state can translate
 521 into biases in the fitted threshold. This provides a model-based diagnostic of the proposed
 522 constraint, rather than evidence that the thresholds represent physical limits. The historical
 523 simulations end in 2014 and therefore exclude the 2015/16 and 2026 events. Moreover, As only
 524 one ensemble member is analysed per model, these results do not establish whether threshold
 525 crossings would occur in other realisations of the same model.

526 The models also allow us to test the association between gradient depletion and subsequent
 527 growth during the growth season, for which the observational record provides no near-zero-
 528 gradient cases (Table S18). We use up to three members per model, giving 145 model-member
 529 simulations across the 57 models. We consider two definitions of a near-zero gradient: the fixed



530 threshold of 0.3°C used in the main analysis, and a model-specific threshold obtained by scaling
531 0.3°C by the ratio of the standard deviation of each simulation's gradient anomalies to that of
532 ERSSTv5 over 1950–2014.

533 Using the fixed 0.3°C criterion, we identify 1,873 months with Niño3.4 above $+1^{\circ}\text{C}$ and a
534 model-specific gradient below 0.3°C , across 39 models. Of these, 201 months in 16 models occur
535 during September–December. Niño3.4 increases in the following month in 59 of these 201 cases
536 (29%; 95% confidence interval, 23–36%). By comparison, it increases in 695 of 1,124 months
537 (62%; 59–65%) during the same season when Niño3.4 is above $+1^{\circ}\text{C}$ but $1\text{--}2^{\circ}\text{C}$ of gradient
538 remains. The contrast is larger in October–November: subsequent growth occurs in 17 of 82 near-
539 zero-gradient cases (21%), compared with 363 of 496 cases with $1\text{--}2^{\circ}\text{C}$ of gradient remaining
540 (73%).

541 From January to May, when strong El Niño events typically decay, the difference is much
542 smaller: Niño3.4 increases in 345 of 1,495 near-zero-gradient cases (23%), compared with 697 of
543 2,451 cases with $1\text{--}2^{\circ}\text{C}$ of gradient remaining (28%). Giving each model equal weight rather than
544 weighting individual months equally yields corresponding growth fractions of 0.33 and 0.58 for
545 September–December. Thus, in the coupled models, near-zero gradients are associated with a
546 substantially lower probability of further Niño3.4 growth during the growth season, whereas the
547 contrast is weaker during the usual decay season.

548

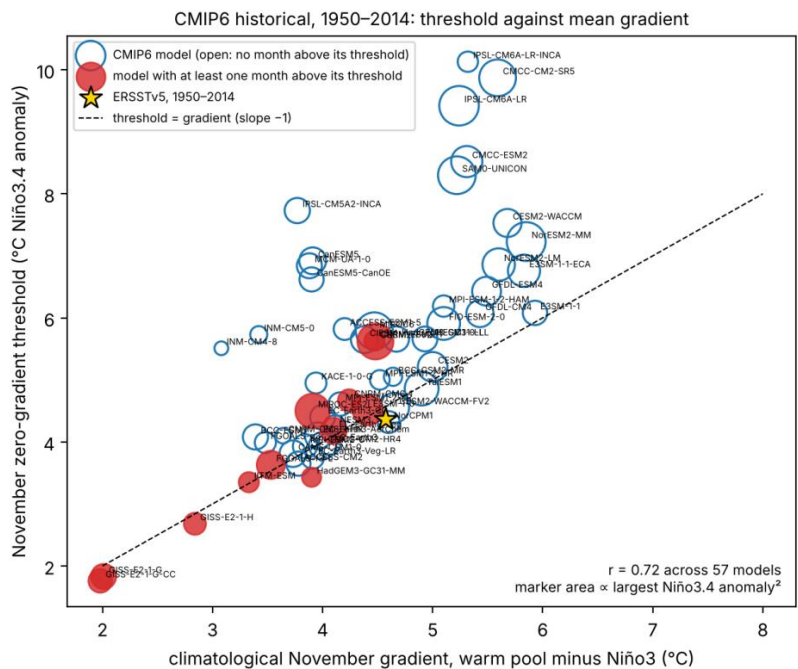


Figure 6. The November zero-gradient threshold of each CMIP6 model against its climatological November gradient, both from the model's own historical simulation for 1950–2014 (one member per model), with ERSSTv5 over the same years. Marker size is proportional to the largest monthly Niño3.4 anomaly in the simulation, and filled markers are models in which at least one month exceeded the threshold for its calendar month. The line is the one-to-one relation that a slope of exactly -1 would give.

4 Discussion and Conclusions

The fitted zero-gradient threshold identifies a candidate constraint on El Niño amplitude, rather than a prediction of an individual event's peak. Historical Niño3.4 anomalies remained below their calendar-month thresholds, but this non-exceedance does not establish a universal physical ceiling. Events can peak while retaining a substantial zonal SST gradient, as in 2015/16 and 2023/24, whereas eastern Pacific-centred events can approach zero gradient at lower anomalies than the fitted relationship predicts.

The distinction between a statistical diagnostic and a dynamical constraint is essential. The near-unit negative slope arises partly because Niño3 and Niño3.4 share a strong SST signal while



566 warm-pool SST varies comparatively little. The physical significance of this relationship therefore
 567 depends on what happens as the observed gradient becomes small, not on the contemporaneous
 568 correlation alone. The historical association between near-zero gradients and subsequent
 569 weakening is consistent with growth arrest, but all qualifying months occurred between January
 570 and May. The observations cannot distinguish a gradient-imposed constraint from the seasonal
 571 termination of strong events.

572 The fitted threshold also involves extrapolation, particularly in autumn, when no observed
 573 anomaly has approached the estimated zero crossing. Atmospheric responses or damping at high
 574 SST could alter the relationship near that crossing (Ramanathan and Collins, 1991; Takahashi and
 575 Dewitte, 2016), but the historical linear relationship does not determine the direction or magnitude
 576 of such departures. The growth-arrest test avoids extrapolating the regression: it evaluates
 577 subsequent Niño3.4 changes after the observed gradient meets a specified criterion. Nevertheless,
 578 this remains an observational test and cannot, by itself, isolate the underlying heat-budget terms.

579 Dataset and methodological choices introduce additional uncertainty. OISST places the
 580 1982/83 and 2015/16 peaks 0.1–0.5°C above ERSSTv5. Refitting over the satellite-era comparison
 581 period gives a November threshold of +4.2°C in OISST, compared with +4.0°C in ERSSTv5 over
 582 the same period (Table S5). Regional definitions and regression choices contribute uncertainty
 583 beyond the bootstrap intervals (Section 3.1). Nevertheless, the relationship between event centring
 584 and gradient residual, and the absence of a statistically resolved change in the ERSSTv5 tropical-
 585 relative threshold, persist across the tested regional boxes that do not overlap Niño3.4 (Table S4).

586 Several processes could sustain warming after the zonal SST gradient becomes small. If the
 587 warm pool remains warm, a larger Niño3.4 anomaly can develop before the observed gradient
 588 vanishes, consistent with the positive residuals of 2015/16 and 2023/24. A nonlinear atmospheric
 589 response could further amplify strong events as convection extends into the eastern Pacific
 590 (Takahashi and Dewitte, 2016; Cai et al., 2018). Thermocline adjustment, ocean advection and
 591 surface heat fluxes also need not vanish when a regional SST difference reaches zero. The record
 592 recharge of 2026 could warm the eastern Pacific after the surface gradient has gone, because tilt
 593 and basin-wide heat content are distinct responses to the wind (Clarke, 2010). The 2026 budget,
 594 carried through the peak, will show which.

595 Ocean heat storage is particularly relevant to the 2026 event. The record recharge could sustain
 596 eastern Pacific warming after the surface gradient has substantially weakened. Thermocline tilt



597 and basin-wide heat content represent related but distinct aspects of the ocean response to wind
598 forcing (Clarke, 2010). A small tilt does not imply that the ocean has exhausted its heat supply.
599 The heat budget in Sect. 3.2 shows that the two advective feedback terms reversed in the historical
600 near-zero-gradient months, but reached record strength in July–September 2026. Extending the
601 budget analysis through the event peak will show whether stored ocean heat sustains the peak or
602 supports further warming.

603 A sustained reversal of the zonal gradient would pose a further challenge to a simple ceiling
604 interpretation. Simulations under much warmer climates can develop a reorganised tropical
605 circulation, including equatorial superrotation (Tziperman and Farrell, 2009; Caballero and Huber,
606 2010), but these states should not be equated with a brief reversal of a regional SST gradient. Since
607 1950, the ERSSTv5 gradient has been negative in only three months, by at most 0.25°C ,
608 comparable to the 0.22°C inter-product difference. Winds remained easterly during those months.
609 The prospective growth-arrest test therefore focuses on whether Niño3.4 continues to increase after
610 the gradient becomes near zero, but it does not test whether the gradient can reverse.

611 Nor does the mean state reliably predict the amplitude at which an individual event will peak
612 below the fitted threshold. An exploratory analysis of 31 warm episodes since 1870, each with a
613 monthly maximum of at least $+1^{\circ}\text{C}$, uses the preceding three-year mean gradient and warm-pool
614 temperature together with event centring at the peak. Leave-one-out correlations are 0.22 for linear
615 regression and 0.06 for a Gaussian process, with errors no smaller than the spread of observed
616 peaks (Figures S5 and S6). Because event centring at the peak is included, this is a diagnostic
617 analysis rather than an operational forecast. Its weak performance reinforces the distinction
618 between a proposed upper constraint and the prediction of individual event amplitudes.

619 Coupled-model tests of the threshold itself are given in Sect. 3.6. Long simulations could
620 establish whether growth after near-zero gradients occurs more frequently than the short
621 observational record suggests and help separate seasonal evolution from the proposed constraint.
622 Targeted analyses of wind stress, ocean heat transport and surface heat exchange would help
623 determine whether the fitted SST threshold corresponds to a weakening of the net positive
624 feedback. Results from much warmer climates motivate this investigation (Geng et al., 2024), but
625 do not validate the proposed present-day threshold.

626 If supported, the proposed constraint would link the upper range of El Niño amplitude to the
627 tropical Pacific mean state, particularly warm-pool temperature relative to tropical-mean SST.



628 Such a relationship could provide information beyond the limited observational sampling of rare
629 extremes. It would also motivate examining whether low-order models omit a state-dependent
630 limitation on growth when unusually strong stochastic forcing is required to reproduce observed
631 extremes. At present, the observations identify a candidate seasonal constraint and specify
632 outcomes that could contradict it. The 2026 event offers a prospective test, not a definitive
633 demonstration of a ceiling.

634

635 **Code and data availability**

636 ERSSTv5, COBE-SST2, OISST v2 and GODAS are available from NOAA PSL
637 (<https://psl.noaa.gov/data/gridded/>), HadISST1 from the Met Office Hadley Centre
638 (<https://www.metoffice.gov.uk/hadobs/hadisst/>), weekly Niño-region SST from NOAA CPC
639 (<https://www.cpc.ncep.noaa.gov/data/indices/wksst9120.for>), warm water volume from NOAA
640 PMEL (<https://www.pmel.noaa.gov/tao/wwv/>), the NCEP–NCAR, NCEP–DOE and 20CRv3
641 reanalyses from NOAA PSL (<https://psl.noaa.gov/data/gridded/>) and CMIP6 output from the
642 Pangeo cloud archive (<https://pangeo-data.github.io/pangeo-cmip6-cloud/>) and ESGF. Analysis
643 and figure scripts, and the pre-registration of the tests in Table 1, are deposited on Zenodo (DOI
644 to be added at submission).

645

646 **Author contributions**

647 IC and EKS conceived the study. IC designed and conducted the analysis and wrote the first draft.
648 MB, MP, ND and MC contributed to the development of the analysis and to the revision of the
649 manuscript. All authors discussed the results and approved the final manuscript.

650

651 **Competing interests**

652 The authors declare that they have no conflict of interest.

653

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661

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665

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