

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

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Introduction

This Supplementary Information gives the zero-gradient threshold for each calendar month in the SST datasets, the sensitivity tests, the values for individual events, the prospective tests against the 2026 event, the heat budget of the exhausted months and the same fit and growth-arrest test in coupled models, as referred to in the main text. All quantities are computed from ERSSTv5 (Huang et al., 2017) unless stated. COBE-SST2 (Hirahara et al., 2014), HadISST1 (Rayner et al., 2003), OISST v2 (Reynolds et al., 2002), the warm water volumes of NOAA PMEL (Meinen and McPhaden, 2000), NCEP GODAS (Behringer and Xue, 2004) and CMIP6 output (Eyring et al., 2016) are used where named. Methods are as in Sect. 2 of the main text. Fits use 1950–2025, anomalies are relative to 1991–2020, and ranges are 5–95% intervals from a block bootstrap with 36-month blocks and 2000 resamples (600 for the 30-year windows of Fig. 3a), drawn independently for each period.

Text S1. Extended discussion

The passages below extend the discussion in the main text and are kept here so that the full argument is on record.

S1.1 Processes limiting event amplitude, and the two roles of the mean gradient (Sect. 1)

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

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

climate, it motivates asking whether gradient depletion could constrain event growth under present-day conditions.

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

S1.2 Direction of regression (Sect. 3.1)

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

S1.3 The seasonal contrast (Sect. 3.2)

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

S1.4 Why the two prospective tests are complementary (Sect. 3.5)

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

S1.5 Statistical diagnostic and dynamical constraint (Sect. 4)

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 warm-pool SST varies comparatively little. The physical significance of this relationship therefore depends on what happens as the observed gradient becomes small, not on the

contemporaneous correlation alone. The historical association between near-zero gradients and subsequent weakening is consistent with growth arrest, but all qualifying months occurred between January and May. The observations cannot distinguish a gradient-imposed constraint from the seasonal termination of strong events.

S1.6 Extrapolation, and processes that could sustain warming (Sect. 4)

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

Several processes could sustain warming after the zonal SST gradient becomes small. If the warm pool remains warm, a larger Niño3.4 anomaly can develop before the observed gradient vanishes, consistent with the positive residuals of 2015/16 and 2023/24. A nonlinear atmospheric response could further amplify strong events as convection extends into the eastern Pacific (Takahashi and Dewitte, 2016; Cai et al., 2018). Thermocline adjustment, ocean advection and surface heat fluxes also need not vanish when a regional SST difference reaches zero.

Ocean heat storage is particularly relevant to the 2026 event. The record recharge could sustain eastern Pacific warming after the surface gradient has substantially weakened. Thermocline tilt and basin-wide heat content represent related but distinct aspects of the ocean response to wind forcing (Clarke, 2010). A small tilt does not imply that the ocean has exhausted its heat supply. The heat budget of Text S2 shows that the two local feedbacks reversed in the historical exhausted months and were at record strength in July–September 2026; whether stored heat prolongs the 2026 peak or supports further growth will be seen in the same budget carried through the peak.

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

S1.7 Dataset and methodological uncertainty (Sect. 4)

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

S1.8 Predicting individual peaks from the mean state, and model tests (Sect. 4)

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

Coupled-model tests of the threshold are reported in Text S3. Long simulations can also establish whether growth after near-zero gradients occurs more often than the short observational record suggests, and so help separate seasonal evolution from the proposed constraint. Results from much warmer climates motivate this investigation (Geng et al., 2024), but do not validate the proposed present-day threshold.

Text S2. Heat budget of the Niño3 mixed layer in the exhausted months

We use NCEP GODAS (Behringer and Xue, 2004), monthly means from January 1980 to September 2026, on its 1° by 1/3° grid with 10 m levels in the upper ocean. The budget is that of the mean temperature T_a of the 0–50 m layer over Niño3 (5°S–5°N, 150°–90°W): $\partial T_a / \partial t = -u\partial T/\partial x - v\partial T/\partial y - w\partial T/\partial z + Q/(\rho c_p H) + R$, with $H = 50$ m, $\rho = 1025$ kg m⁻³ and $c_p = 3990$ J kg⁻¹ K⁻¹. Each advective term is formed at every grid point and level from the monthly-mean fields, averaged over the five levels in 0–50 m (5 to 45 m) and then area-averaged with cosine weights. Horizontal velocities are interpolated from the B-grid to tracer points as the mean of the four surrounding values, and the vertical velocity, held at the interfaces between levels, is interpolated to the levels with $w = 0$ at the surface. Q is the GODAS net surface heat flux (positive into the ocean; its 1980–2025 Niño3 mean is +65 W m⁻²). The tendency is a centred difference of the monthly means. The residual R holds sub-monthly covariances, which include tropical instability waves, vertical mixing and the assimilation increment.

Anomalies are relative to the 1980–2025 climatology of each calendar month. The zonal and vertical advection anomalies are split into a mean-flow part ($-\bar{u}\partial T'/\partial x$ and $-\bar{w}\partial T'/\partial z$), an anomalous-flow part ($-u'\partial \bar{T}/\partial x$ and $-w'\partial \bar{T}/\partial z$) and a nonlinear part. The zonal advective feedback of the main text is $-u'\partial \bar{T}/\partial x$ and the thermocline feedback is $-\bar{w}\partial T'/\partial z$; the Ekman

feedback $-w'\partial\bar{T}/\partial z$ is listed in Table S16 but is not part of the sum shown in Fig. 5. Table S16 gives the means over the growth season (July–November of the onset year) and over the months with an ERSSTv5 gradient below $0.3\text{ }^{\circ}\text{C}$ for each event, and the composite of Fig. 5d bins every month with Niño3.4 above $+1\text{ }^{\circ}\text{C}$ from 1980 to 2025 by gradient.

Two limitations apply. The residual is large in some decay months, when tropical instability waves resume and the monthly means no longer capture the eddy heat flux; this affects the meridional term and the residual, not the two feedback terms. And the budget, like the SST record, cannot by itself separate the gradient from the season, because every exhausted month fell between January and May. What it adds is the sign of the feedbacks in those months: the sum of the two terms that drive growth was negative in all 11 exhausted months (-0.08 to -1.49 K per month) and the zonal advective term in all 11, with event means of -0.9 to -1.0 K per month in 1983 and 1998, and in July–September 2026 they summed to $+1.5\text{ K per month}$, the largest three-month value in the record, against a surface-flux anomaly of -0.9 K per month , the most negative in the record.

Text S3. The fit in CMIP6 historical simulations

We apply the fit of the main text to 57 CMIP6 models (Eyring et al., 2016) with monthly tos in the historical experiment, read from the Pangeo cloud archive, one member per model, for 1950–2014, with anomalies relative to each model's own climatology for those years and ERSSTv5 fitted over the same years. The slopes lie between -1.14 and -0.49 (median -0.87 ; ERSSTv5 -1.05), 34 of the 57 within 0.2 of the observed value, and the within-month correlations between -0.96 and -0.61 (median -0.88 ; ERSSTv5 -0.90). The November threshold ranges from $+1.76$ to $+10.13\text{ }^{\circ}\text{C}$ (median $+5.05\text{ }^{\circ}\text{C}$; ERSSTv5 $+4.37\text{ }^{\circ}\text{C}$) and is set by the climatological November gradient, which ranges from 1.98 to $5.93\text{ }^{\circ}\text{C}$ (correlation between threshold and gradient across models 0.72 ; between threshold and slope 0.83). The median April threshold is $+2.88\text{ }^{\circ}\text{C}$. The scatter of threshold against climatological gradient is Fig. 6 of the main text.

12 models (CESM2-FV2, CNRM-CM6-1, CNRM-ESM2-1, E3SM-1-0, EC-Earth3-Veg, FGOALS-f3-L, GISS-E2-1-G-CC, GISS-E2-1-G, GISS-E2-1-H, HadGEM3-GC31-MM, IITM-ESM, MIROC-ES2L) produced a month above the threshold for its calendar month, 259 months in all, although the largest Niño3.4 anomalies reach $+2.9\text{ }^{\circ}\text{C}$ in the median model and exceed $+3\text{ }^{\circ}\text{C}$ in 24 models. A model's threshold is therefore not a fixed temperature but the gradient its own mean state provides divided by the rate at which its events consume it, which is what the observational threshold claims to be. The models with the weakest climatological gradients carry the lowest thresholds, and a system whose mean gradient is biased carries a biased threshold; this is the operational diagnostic of the Discussion. The historical simulations end in 2014, so they do not include the 2015/16 or 2026 events, and the one-member sample does not test whether a longer simulation would eventually cross the threshold.

The models also allow the growth-arrest test of Table 1 to be run in the growth season, where the observations have no case (Table S18). We use up to three members per model, 145 simulations of 57 models in all, and two near-zero criteria: the fixed $0.3\text{ }^{\circ}\text{C}$ of the main text,

and 0.3 °C scaled by the ratio of each simulation's to ERSSTv5's standard deviation of gradient anomalies over 1950–2014. With the fixed criterion there are 1873 months with Niño3.4 above +1 °C and less than 0.3 °C of the model's own gradient, in 39 models; 201 of them, in 16 models, fall in September–December. Of those, 59 were followed by a rise in Niño3.4 (29%, 95% Wilson interval 23–36%), against 695 of 1124 months in the same season and with the same anomaly but 1–2 °C of gradient left (62%, 59–65%). In October–November the figures are 17 of 82 (21%) against 363 of 496 (73%). From January to May, when strong events decay in any case, an exhausted gradient makes no difference: 345 of 1495 (23%) against 697 of 2451 (28%). Weighting each model equally rather than each month gives 0.33 against 0.58 in September–December.

The cases are unevenly distributed. GISS-E2-1-G, GISS-E2-1-G-CC and IITM-ESM, whose climatological gradients are the weakest in the set, supply 92 of the 201 September–December cases. Without them 47 of 109 rose (43%, 34–52%) against 652 of 1019 (64%) in their control, in 13 models. With the scaled criterion the September–December fractions are 35% (87 of 249; 29–41%) for all models and 50% (70 of 141; 42–58%) without the three weak-gradient models, against 62% and 64%. The models therefore separate the gradient from the season in the direction the threshold predicts in every cut of the sample, but the size of the effect depends on the cut: it is large in the weak-gradient models, where the gradient runs out often, and smaller, though still present, in the rest, where it runs out rarely. Exhaustion does not stop every event. The historical simulations end in 2014, so they contain neither the 2015/16 nor the 2026 event, and the scaled criterion is a first approximation to the inter-model difference in gradient variability.

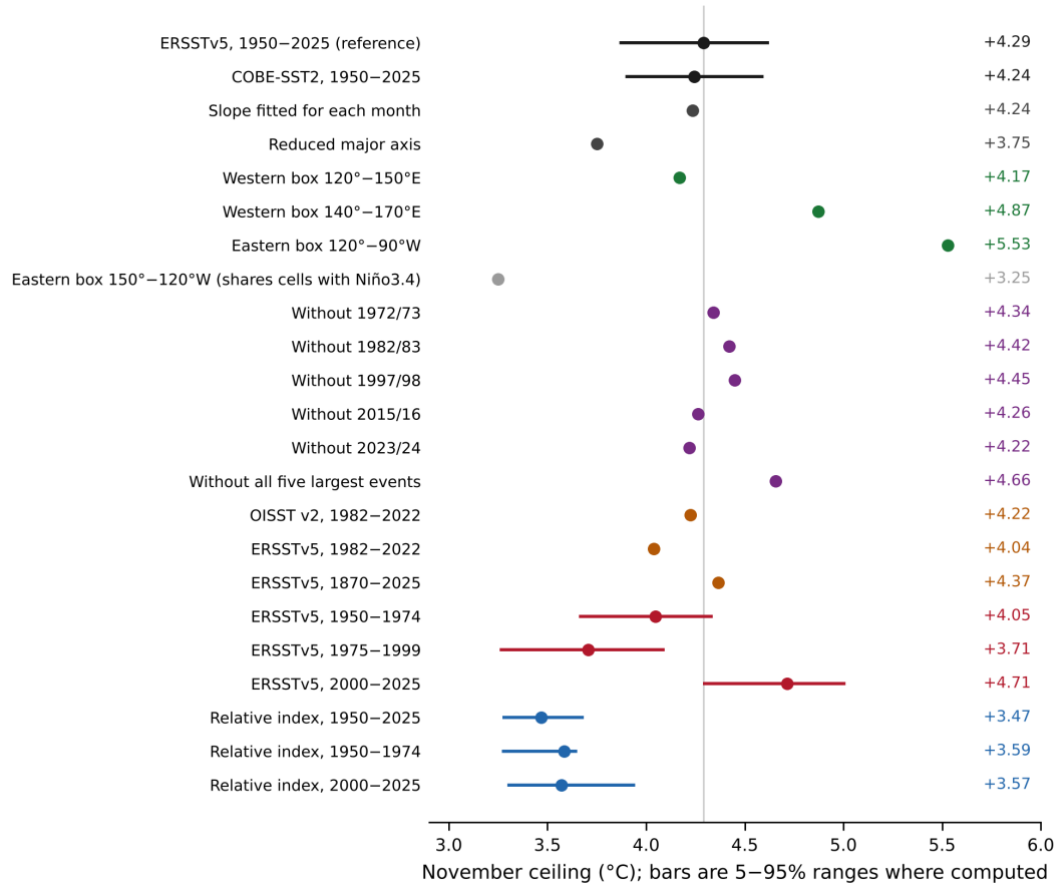


Figure S1. The November threshold under alternative choices of dataset, fitting method, boxes, record length and period, with single events removed, and in relative units. Bars are 5–95% ranges from the block bootstrap, where computed. The eastern box at 120°–90°W shares no grid cell with Niño3.4. The vertical line marks the reference value, +4.29 °C (ERSSTv5, 1950–2025, Niño3 and the 130°–160°E warm pool, one slope with an intercept for each calendar month).

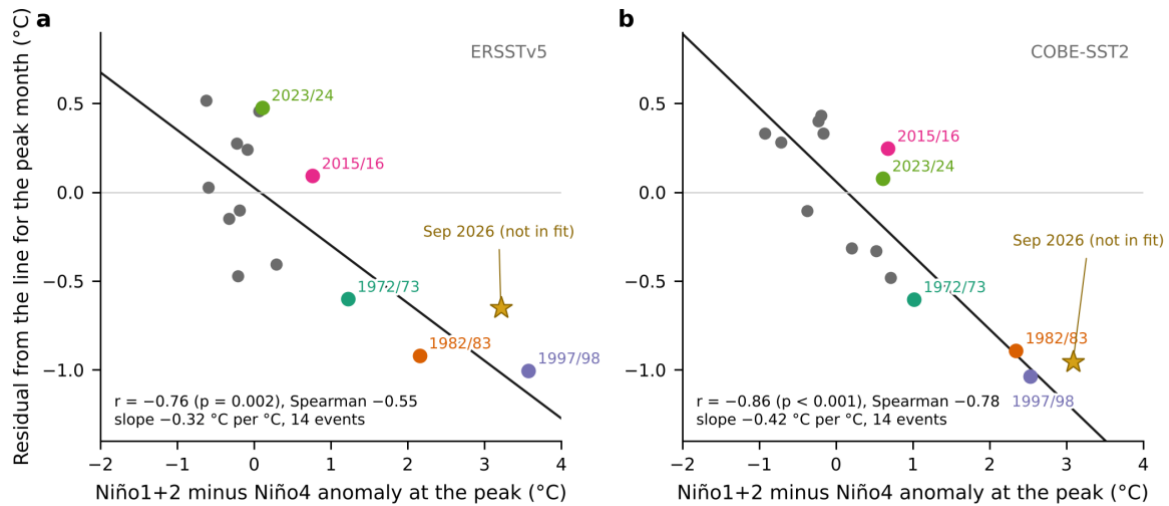


Figure S2. For every El Niño since 1950 with a monthly Niño3.4 peak of at least +1 °C, the gradient remaining at the peak, measured from the line for the peak month, against the eastward centring of the event (Niño1+2 minus Niño4 anomaly at the peak), in (a) ERSSTv5 and (b) COBE-SST2. The five largest events are coloured as in Figure 1. September 2026 is shown but is not used in the fit.

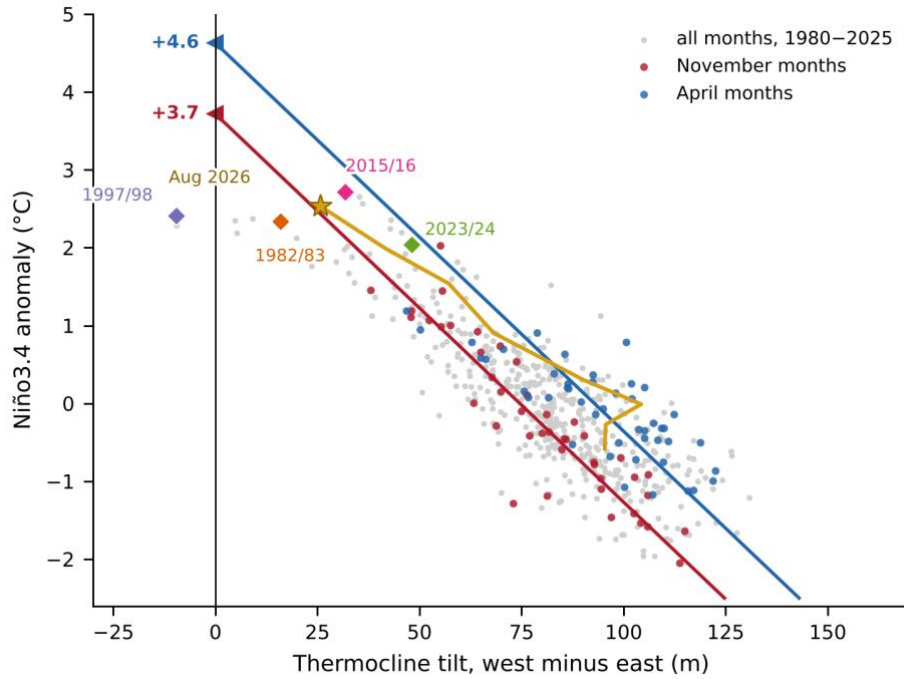


Figure S3. The Niño3.4 anomaly against the zonal thermocline tilt (mean 20 °C-isotherm depth west of 155°W minus that east of it) for every month from January 1980 to December 2025, oriented as Figure 1a. November and April months are coloured. Their lines are the least-squares fit of the tilt on the anomaly, with one slope and an intercept for each calendar month, and the anomaly at which each line reaches zero tilt is marked. The four largest events since 1980 are marked at their peaks, and the 2026 path runs from January to August.

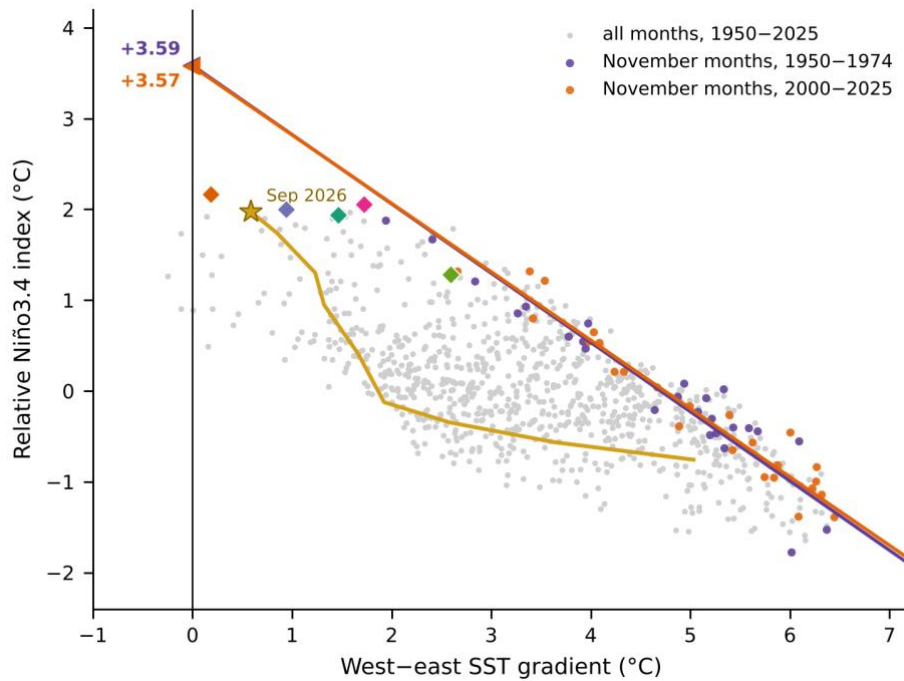


Figure S4. The relation of Figure 1a with the Niño3.4 anomaly replaced by the relative index (Niño3.4 minus the 20°S–20°N ocean-mean anomaly). November months of 1950–1974 and 2000–2025 are coloured, with the November line of each period from its own fit and the anomaly at which it reaches zero gradient. The five largest events are marked at their peaks (colours as in Figure 1), and the 2026 path runs from January to September.

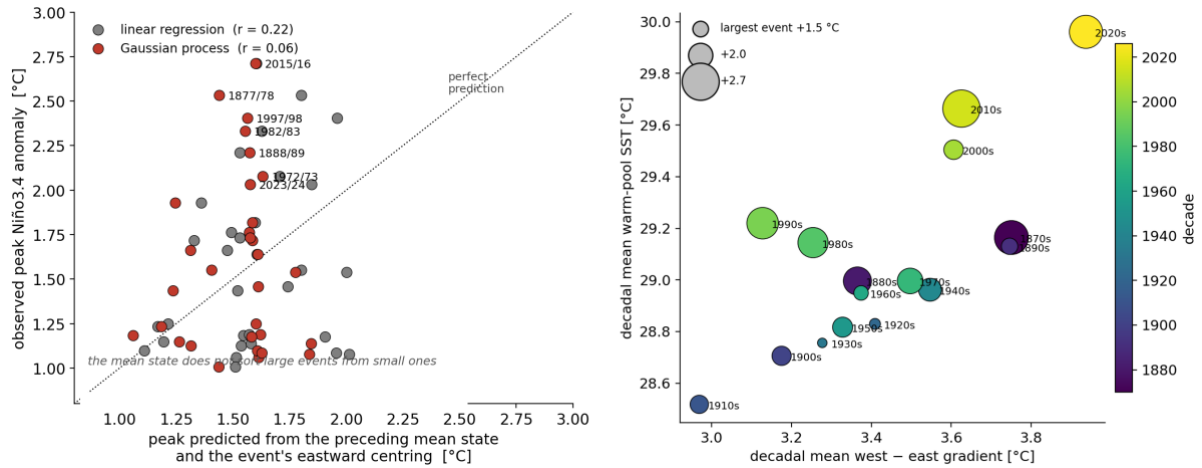


Figure S5. (Left) Leave-one-out predictions of the peak Niño3.4 anomaly of the 31 warm episodes since 1870 with a monthly maximum of at least +1 °C (a looser definition than the 14 events since 1950 of Section 2 of the main text), from the mean west–east gradient and warm-pool temperature of the three years before each event and the eastward centring at its peak, by linear regression and by Gaussian-process regression. (Right) The mean state of each decade since the 1870s, as decadal mean gradient against decadal mean warm-pool SST, with marker size proportional to the largest monthly Niño3.4 anomaly of the decade and colour by decade.

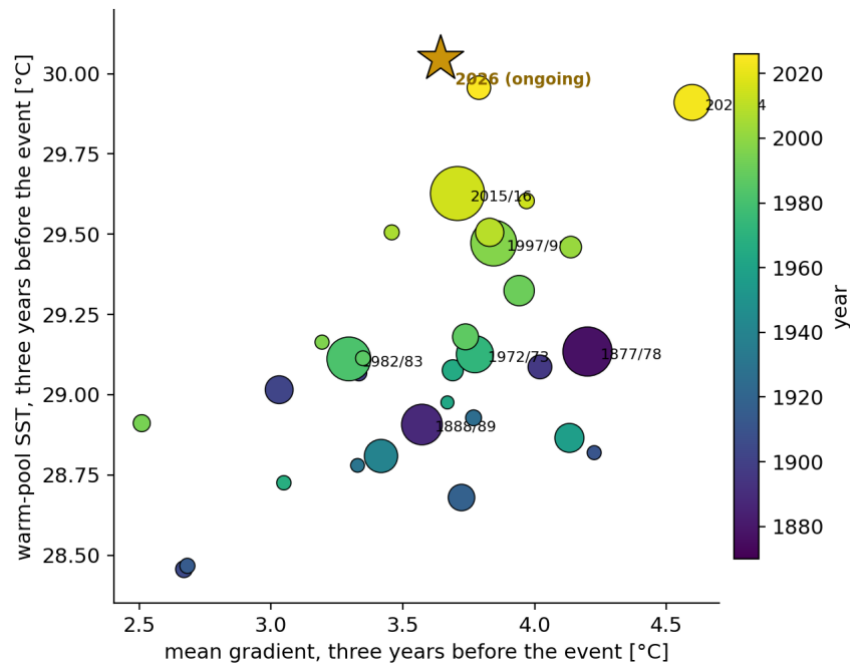


Figure S6. The 31 warm episodes since 1870 with a monthly Niño3.4 maximum of at least +1 °C, as in Figure S5, placed by the mean gradient and warm-pool SST of the three years before each, with marker size proportional to the peak anomaly and colour by year. The largest events are labelled. The 2026 event is placed by its 2023–2025 mean state.

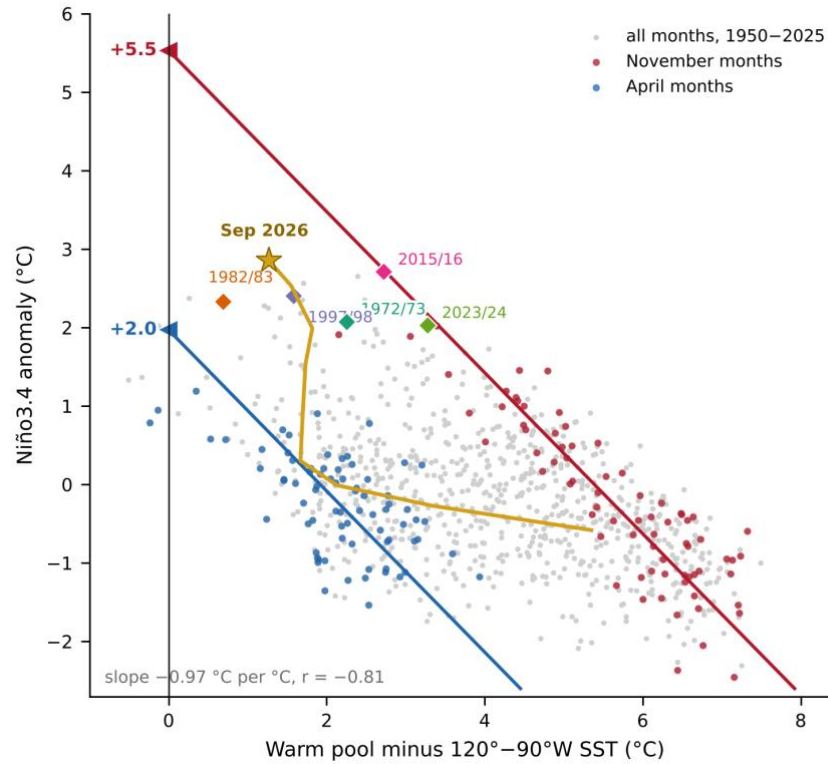


Figure S7. The relation of Figure 1a with the eastern box replaced by 120°–90°W (242°–270°E on the ERSSTv5 grid), which shares no grid cell with Niño3.4. Lines and symbols as in Figure 1a. The common slope is -0.97 °C per °C with $r = -0.81$ after removing the seasonal cycle; the November threshold is $+5.53\text{ °C}$ (5–95% range $+4.90$ to $+6.11\text{ °C}$) and the April threshold $+1.97\text{ °C}$. No month from 1950 to 2025 exceeded the threshold for its calendar month, and 8 months had less than 0.3 °C of this gradient.

Table S1. The zero-gradient threshold for each calendar month in the two datasets, 1950–2025 (°C; 5–95% ranges from the block bootstrap)

Month	Mean gradient, ERSSTv5	Threshold, ERSSTv5	Threshold, COBE-SST2	Relative threshold, ERSSTv5	Relative threshold, COBE-SST2
Jan	3.65	+3.40 (+3.09 to +3.66)	+3.46 (+3.19 to +3.75)	+2.79 (+2.64 to +2.96)	+2.92 (+2.76 to +3.11)
Feb	2.75	+2.53 (+2.30 to +2.73)	+2.65 (+2.44 to +2.87)	+2.11 (+2.00 to +2.24)	+2.27 (+2.15 to +2.41)
Mar	2.11	+1.89 (+1.69 to +2.07)	+1.94 (+1.76 to +2.12)	+1.62 (+1.53 to +1.73)	+1.72 (+1.61 to +1.83)
Apr	2.06	+1.76 (+1.56 to +1.94)	+1.70 (+1.53 to +1.87)	+1.52 (+1.43 to +1.62)	+1.52 (+1.43 to +1.63)
May	2.56	+2.24 (+1.99 to +2.44)	+2.22 (+2.01 to +2.42)	+1.89 (+1.78 to +2.01)	+1.93 (+1.82 to +2.06)
Jun	2.98	+2.68 (+2.38 to +2.89)	+2.67 (+2.42 to +2.92)	+2.23 (+2.09 to +2.37)	+2.29 (+2.15 to +2.44)
Jul	3.48	+3.16 (+2.83 to +3.42)	+3.16 (+2.88 to +3.45)	+2.60 (+2.45 to +2.77)	+2.68 (+2.51 to +2.86)
Aug	4.00	+3.69 (+3.32 to +3.97)	+3.69 (+3.37 to +4.00)	+3.01 (+2.84 to +3.21)	+3.10 (+2.91 to +3.30)
Sep	4.36	+4.05 (+3.66 to +4.46)	+4.08 (+3.74 to +4.42)	+3.29 (+3.11 to +3.50)	+3.41 (+3.21 to +3.62)
Oct	4.55	+4.22 (+3.82 to +4.65)	+4.24 (+3.89 to +4.60)	+3.42 (+3.24 to +3.64)	+3.55 (+3.34 to +3.78)
Nov	4.63	+4.29 (+3.87 to +4.71)	+4.24 (+3.90 to +4.59)	+3.47 (+3.28 to +3.68)	+3.55 (+3.36 to +3.78)
Dec	4.37	+4.08 (+3.69 to +4.48)	+4.07 (+3.76 to +4.40)	+3.31 (+3.14 to +3.50)	+3.42 (+3.24 to +3.64)

Common slope -1.03 °C per °C in ERSSTv5 and -1.05 in COBE-SST2. The correlation within months is -0.88 and -0.90 , against -0.65 and -0.66 when all months are pooled. In relative units the slopes are -1.34 and -1.31 . The mean gradient is the 1950–2025 mean for the month.

Table S2. The relation on the extended ERSSTv5 record, by period

Period	Slope (°C per °C)	November threshold (°C)	Relative November threshold (°C)	Mean gradient (°C)	Largest monthly Niño3.4 (°C)
1870–1899	−1.02	+4.05	+3.76	3.62	+2.53
1900–1924	−1.01	+3.70	+3.56	3.17	+1.72
1925–1949	−0.96	+4.12	+3.69	3.38	+1.93
1950–1974	−1.03	+4.05	+3.59	3.41	+2.08
1975–1999	−1.14	+3.71	+3.32	3.22	+2.40
2000–2025	−1.03	+4.71	+3.57	3.73	+2.71

Fitted on all months from 1870, the November threshold is +4.37 °C. From 1900 it is +4.43 °C, and from 1950 +4.29 °C. Values before 1950 rest on sparse in-situ coverage and are shown as a check only. Measured against the 1950–2025 thresholds, the only earlier month to reach the threshold for its calendar month is February 1878 (+2.53 °C, against a February threshold of +2.53 °C), during the 1877/78 event. In relative units it exceeds the February threshold (+2.18 against +2.11 °C) but lies below its 95th percentile (+2.24 °C). COBE-SST2 has no such month before 1950.

Table S3. The November threshold by period, with and without the years of the five largest events (°C; 5–95% ranges)

Period	Niño3.4 units, ERSSTv5	Events removed	COBE-SST2	Relative, ERSSTv5	Events removed	Relative, COBE-SST2	Mean gradient	Warm-pool SST	Tropical-mean anomaly
1950–1974	+4.05 (+3.67 to +4.33)	+4.25	+3.94	+3.59 (+3.28 to +3.64)	+3.65	+3.42	3.41	28.91	−0.49
1975–1999	+3.71 (+3.27 to +4.09)	+4.33	+3.78	+3.32 (+2.98 to +3.68)	+3.76	+3.49	3.22	29.15	−0.22
2000–2025	+4.71 (+4.30 to +5.00)	+4.95	+4.76	+3.57 (+3.31 to +3.94)	+3.91	+3.69	3.73	29.68	+0.09
2000–2025 minus 1950–1974	+0.67 (+0.17 to +1.16)		+0.82 (+0.35 to +1.26)	−0.01 (−0.21 to +0.52)		+0.27 (−0.02 to +0.75)			

Probability of no rise between the first and last periods: 0.018 (Niño3.4 units) and 0.303 (relative) in ERSSTv5, and 0.002 and 0.066 in COBE-SST2, with the bootstrap drawn independently for each period. Event years removed: 1972–1973, 1982–1983, 1997–1998, 2015–2016, 2023–2024. Mean gradient, warm-pool SST and tropical-mean anomaly are ERSSTv5 period means.

Table S4. Sensitivity to the western box, 1950–2025 (eastern box: Niño3)

Western box	Mean gradient (°C)	Slope (°C per °C)	November threshold, ERSSTv5 (°C)	April threshold, ERSSTv5 (°C)	November threshold, COBE-SST2 (°C)	Change in November threshold, 2000–2025 minus 1950–1974, Niño3.4 units (°C)	Change, relative units (°C)
120°–150°E	3.28	−1.04	+4.17	+1.69	+4.00	+0.44 (+0.04 to +0.82)	−0.20 (−0.39 to +0.25)
130°–160°E (used)	3.46	−1.03	+4.29	+1.76	+4.24	+0.67 (+0.17 to +1.16)	−0.01 (−0.21 to +0.52)
140°–170°E	3.51	−0.91	+4.87	+1.93	+4.87	+1.19 (+0.23 to +2.30)	+0.41 (−0.07 to +1.39)
Niño4, 160°E–150°W	2.61	−0.28	not defined	not defined	not defined	–	–

The Niño4 region warms during El Niño (slope −0.28), so it is not a fixed reference for the contrast and its zero lies far outside the data. Changes are ERSSTv5 with 5–95% ranges from bootstraps drawn independently for each period. In relative units the change has zero inside its range for every box. For the eastern box at 120°–90°W of Table S5 the changes are +0.67 (−0.05 to +1.85) and −0.02 (−0.42 to +1.11) °C.

Table S5. Sensitivity to the eastern box, to single events, to the fitting method and to the dataset (1950–2025 unless stated)

Test	Slope (°C per °C)	November threshold, ERSSTv5 (°C)	April threshold, ERSSTv5 (°C)	November threshold, COBE-SST2 (°C)
Eastern box 150°–90°W (Niño3, used)	–1.03	+4.29	+1.76	+4.24
Eastern box 120°–90°W, no grid cell shared with Niño3.4	–0.97	+5.53	+1.97	+5.44
Eastern box 150°–120°W, the part shared with Niño3.4	–1.09	+3.25	+1.59	+3.17
Without 1972/73	–1.03	+4.34		+4.30
Without 1982/83	–1.01	+4.42		+4.35
Without 1997/98	–1.00	+4.45		+4.40
Without 2015/16	–1.04	+4.26		+4.22
Without 2023/24	–1.05	+4.22		+4.18
Without all five	–0.97	+4.66		+4.59
Slope fitted for each month (–0.81 to –1.20)	by month	+4.24	+2.33	+4.44
Reduced major axis	–1.18	+3.75	+1.52	+3.80
Niño3.4 regressed on the gradient (value at zero gradient)	–1.34	+3.28	+1.31	
OISST v2, 1982–2022	–1.12	+4.22		
ERSSTv5, 1982–2022	–1.14	+4.04		

Month-specific slopes: Jan –0.99, Feb –0.88, Mar –0.81, Apr –0.81, May –1.00, Jun –1.08, Jul –1.16, Aug –1.19, Sep –1.20, Oct –1.10, Nov –1.05, Dec –1.04. The reduced-major-axis fit treats the scatter as error in both variables and gives the steeper slope. Niño3.4 regressed on the gradient gives the expected anomaly once the gradient is gone, and three months exceeded it in their calendar month (February 1998, February and March 2016). Its slope is shown as the inverse of the fitted slope, for comparison with the other rows. Within months, the variance of the warm pool about its own fit on Niño3.4 is 73% of that of the gradient. OISST peaks: 1982/83 +2.80 °C with 0.09 °C of gradient, 1997/98 +2.62 °C, 2015/16 +2.84 °C. Regressed separately on Niño3.4 within months, Niño3 rises by 0.98 and the warm pool changes by –0.06 °C per °C (COBE-SST2 0.96 and –0.08).

Table S6. Dependence of the period comparison on the boundary year (November threshold, °C; early period from 1950, late period to 2025)

Boundary	Niño3.4 units, ERSSTv5: early → late	Change	Relative, ERSSTv5: early → late	Change	Change, COBE-SST2, Niño3.4 units	Change, COBE-SST2, relative
1985	+3.89 → +4.26	+0.37	+3.44 → +3.49	+0.05	+0.52	+0.28
1990	+3.93 → +4.23	+0.31	+3.48 → +3.47	–0.01	+0.38	+0.14
1995	+4.03 → +4.39	+0.36	+3.52 → +3.39	–0.13	+0.37	–0.08
2000	+3.89 → +4.71	+0.82	+3.43 → +3.57	+0.14	+0.90	+0.23
2005	+4.04 → +4.64	+0.60	+3.49 → +3.42	–0.07	+0.65	–0.01

The comparison of 1950–1974 with 2000–2025 in the main text is given in Table S3.

Table S7. The five largest events since 1950 at the month of peak Niño3.4 anomaly, and September 2026 (ERSSTv5)

Event	Peak month	Niño3.4 (°C)	Relative (°C)	Niño3 anomaly (°C)	Warm-pool anomaly (°C)	Gradient (°C)	Residual (°C)	Meridional gradient (°C)	Thermocline tilt (m)	Recharge maximum (s.d.), lead	Recharge at peak (s.d.)
1972/73	Dec 1972	+2.08	+1.94	+2.24	−0.77	1.47	−0.60	+0.61	no data	no data	no data
1982/83	Jan 1983	+2.33	+2.16	+2.97	−0.55	0.19	−0.92	−0.96	16	+2.0, 3 months	−0.4
1997/98	Nov 1997	+2.40	+2.00	+3.25	−0.46	0.95	−1.00	+0.13	−10	+2.2, 7 months	+0.4
2015/16	Nov 2015	+2.71	+2.05	+2.83	−0.11	1.72	+0.09	+1.07	32	+1.4, 20 months	+0.3
2023/24	Dec 2023	+2.03	+1.28	+2.02	+0.13	2.59	+0.48	+1.22	48	+1.7, 8 months	−0.4
2026 (ongoing)	Sep 2026	+2.86	+1.97	+3.67	−0.17	0.58	−0.65	+0.80	26 (Aug)	+2.4 in Aug 2026, a record, still rising	—

Residual: gradient minus the line for the peak month. Recharge: the largest standardised warm water volume (1980–2025 base) in the 24 months before the SST peak, and its lead. In COBE-SST2 the residuals are 1972/73 −0.60 (Dec 1972), 1982/83 −0.89 (Jan 1983), 1997/98 −1.04 (Jan 1998), 2015/16 +0.25 (Dec 2015), 2023/24 +0.08 (Nov 2023). The 2026 gradient was 5.03 °C in January and 0.84 °C in August. The September offset from the line is −0.65 °C in ERSSTv5 and −0.96 °C in COBE-SST2, against −1.02 °C predicted from the centring relation of Table S8. The tropical-mean anomaly of +0.88 °C in September exceeds the previous ERSSTv5 record of +0.85 °C in February 2024. In the last week of September the weekly Niño1+2 and Niño4 anomalies were +5.3 and +1.2 °C, against +3.5 and +0.4 °C in the same week of 1997 (NOAA CPC).

Table S8. Every El Niño since 1950 with a monthly peak of at least +1 °C: eastward centring and gradient remaining at the peak

ERSSTv5

Peak month	Niño3.4 (°C)	Niño1+2 minus Niño4 (°C)	Gradient (°C)	Residual (°C)
Jan 1958	+1.76	−0.59	1.72	+0.03
Dec 1963	+1.01	−0.32	3.03	−0.15
Oct 1965	+1.43	−0.21	2.40	−0.47
Dec 1972	+2.08	+1.22	1.47	−0.60
Jan 1983	+2.33	+2.15	0.19	−0.92
Sep 1987	+1.64	+0.29	2.09	−0.40
Jan 1992	+1.82	−0.19	1.54	−0.10
Dec 1994	+1.25	−0.09	3.17	+0.24
Nov 1997	+2.40	+3.57	0.95	−1.00
Nov 2002	+1.46	+0.06	3.39	+0.46
Dec 2006	+1.14	−0.23	3.31	+0.27
Dec 2009	+1.73	−0.63	2.94	+0.52
Nov 2015	+2.71	+0.76	1.72	+0.09
Dec 2023	+2.03	+0.10	2.59	+0.48

COBE-SST2

Peak month	Niño3.4 (°C)	Niño1+2 minus Niño4 (°C)	Gradient (°C)	Residual (°C)
Oct 1951	+1.19	+0.52	2.86	−0.33
Jan 1958	+2.00	−0.71	1.81	+0.28
Nov 1965	+1.68	+0.20	2.36	−0.31
Dec 1972	+1.99	+1.02	1.58	−0.60
Jan 1983	+2.23	+2.34	0.40	−0.89
Sep 1987	+1.39	+0.71	2.34	−0.48
Jan 1992	+1.88	−0.38	1.55	−0.11
Dec 1994	+1.14	−0.17	3.40	+0.33
Jan 1998	+2.59	+2.53	−0.12	−1.04
Nov 2002	+1.49	−0.23	3.28	+0.40
Dec 2006	+1.09	−0.19	3.55	+0.43
Dec 2009	+1.68	−0.93	2.83	+0.33
Dec 2015	+2.85	+0.68	1.53	+0.25
Nov 2023	+2.30	+0.61	2.11	+0.08

Events are runs of at least five months with Niño3.4 at or above +0.5 °C that peak at +1.0 °C or more. Residual against centring: ERSSTv5 $r = -0.76$ ($p = 0.002$), Spearman -0.55 ($p = 0.041$), slope -0.32 °C per °C. COBE-SST2: $r = -0.86$ ($p < 0.001$), Spearman -0.78 ($p = 0.001$), slope -0.42 . In September 2026 the centring is +3.21 °C and the residual -0.65 °C in ERSSTv5. The ongoing event is not in the fit.

Table S9. Months with less than 0.3 °C of gradient, and the growth of strong events by calendar month

(a) ERSSTv5, 1950–2025

Month	Niño3.4 (°C)	Gradient (°C)	Change to the following month (°C)
Jan 1983	+2.33	+0.19	−0.41
Feb 1983	+1.92	−0.12	−0.55
Mar 1983	+1.37	−0.25	−0.42
Apr 1983	+0.95	0.00	−0.04
May 1983	+0.90	+0.20	−0.36
Mar 1992	+1.37	+0.28	−0.18
Apr 1992	+1.19	+0.20	−0.16
Jan 1998	+2.37	+0.14	−0.35
Feb 1998	+2.02	+0.10	−0.69
Mar 1998	+1.33	−0.12	−0.55
Apr 1998	+0.79	+0.15	−0.21

(b) COBE-SST2, 1950–2025

Month	Niño3.4 (°C)	Gradient (°C)	Change to the following month (°C)
Feb 1983	+2.14	−0.14	−0.78
Mar 1983	+1.36	−0.04	−0.54
Apr 1983	+0.83	−0.13	−0.13
Jan 1998	+2.59	−0.12	−0.52
Feb 1998	+2.07	−0.27	−0.63
Mar 1998	+1.44	−0.32	−0.65
Apr 1998	+0.79	+0.01	−0.34

(c) Months followed by a rise in Niño3.4, by calendar month

Month	Above +1.5 °C, ERSSTv5	Above +1.5 °C, COBE-SST2	Above +1.0 °C, ERSSTv5
Jan	0 of 8	0 of 8	1 of 11
Feb	0 of 5	0 of 6	0 of 10
Mar	0 of 1	0 of 1	0 of 5
Apr	–	–	0 of 1
May	–	–	0 of 1
Jun	–	–	2 of 2
Jul	1 of 1	–	4 of 4
Aug	3 of 3	2 of 2	6 of 6
Sep	3 of 4	2 of 2	7 of 8
Oct	4 of 5	4 of 4	5 of 8
Nov	3 of 5	4 of 6	7 of 12
Dec	3 of 7	4 of 9	5 of 14

(d) Sensitivity to the gradient threshold (months with Niño3.4 above +0.5 °C)

Threshold (°C)	ERSSTv5	COBE-SST2
0.00	3 months, 0 rises	6 months, 0 rises
0.20	10 months, 0 rises	7 months, 0 rises
0.30	11 months, 0 rises	7 months, 0 rises
0.40	11 months, 0 rises	9 months, 0 rises
0.50	13 months, 1 rise	10 months, 0 rises
0.75	17 months, 3 rises	15 months, 2 rises
1.00	27 months, 9 rises	24 months, 7 rises

Above +1.5 °C, January to May: 0 of 14 months followed by a rise in ERSSTv5 and 0 of 15 in COBE-SST2. September to November: 10 of 14 and 10 of 12. The root-mean-square difference between the gradients of the two datasets in

months above +1.5 °C is 0.22 °C. The months with 0.4 to 0.75 °C of gradient that were followed by a rise are April 1993, a weak event, and August and September 1997, in its growth season.

Table S10. The meridional gradient (5°–10°N minus 2.5°S–2.5°N, 150°–90°W), 1950–2025

Quantity	ERSSTv5	COBE-SST2
Climatology, all months (°C)	2.14	2.18
Climatology, November (°C)	2.87	2.91
Slope on Niño3.4 (°C per °C)	−0.58	−0.59
Correlation within months	−0.78	−0.77
Anomaly at which it vanishes, Nov (°C)	+4.75	+4.76
Anomaly at which it vanishes, Dec (°C)	+3.88	+4.06
Anomaly at which it vanishes, Jan (°C)	+2.59	+2.75
Anomaly at which it vanishes, Feb (°C)	+1.36	+1.53
Anomaly at which it vanishes, Mar (°C)	+0.78	+0.86
Anomaly at which it vanishes, Apr (°C)	+1.32	+1.34
At the 1972/73 peak (°C)	+0.61 (Dec 1972)	+0.59 (Dec 1972)
At the 1982/83 peak (°C)	−0.96 (Jan 1983)	−0.68 (Jan 1983)
At the 1997/98 peak (°C)	+0.13 (Nov 1997)	−1.03 (Jan 1998)
At the 2015/16 peak (°C)	+1.07 (Nov 2015)	+0.30 (Dec 2015)
At the 2023/24 peak (°C)	+1.22 (Dec 2023)	+0.86 (Nov 2023)
September 2026 (°C)	+0.80	+1.15

No month from November to January has passed the meridional zero for its month. In February and March, when the climatological meridional gradient is weakest, 16 months in ERSSTv5 and 14 in COBE-SST2 did, all but one (March 1987) after the peak of their event.

Table S11. The zonal thermocline tilt (mean 20 °C-isotherm depth, 120°E–155°W minus 155°W–80°W, from the PMEL warm water volumes), 1980–2025

Quantity	Value
Climatological tilt (m)	82
Slope on Niño3.4 (m per °C)	−20.1
Correlation within months (all months pooled)	−0.88 (−0.83)
Anomaly at which the tilt vanishes, November (°C)	+3.72 (+3.21 to +4.21)
Anomaly at which the tilt vanishes, January (°C)	+3.79
Anomaly at which the tilt vanishes, April (°C)	+4.63
SST-gradient ceiling over the same years, November and January (°C)	+4.11, +3.28
Tilt at the 1982/83, 1997/98, 2015/16 and 2023/24 peaks (m)	+16, −10, +32, +48
Tilt in August 2026 (m)	+26
Western 20 °C-isotherm depth: slope (m per °C), minimum (m)	−8.5, 121 (Dec 1997)
Eastern 20 °C-isotherm depth: slope (m per °C)	+11.7
Basin-mean 20 °C-isotherm depth: correlation with Niño3.4	0.11

The fit uses the same calendar-month intercepts and common slope as the SST gradient. The western thermocline never approaches the surface and the basin-mean depth hardly depends on the Niño3.4 anomaly, so the threshold is set by the wind-held tilt, not by the size of the warm-water reservoir.

Table S12. The prospective tests of the proposed constraint against the 2026 event, fixed before the outcome (calibration 1950–2025)

(a) Amplitude test: 95th percentile of the relative threshold

Month	Relative threshold, 95th percentile, ERSSTv5 (°C)	Relative threshold, 95th percentile, COBE-SST2 (°C)	Threshold in Niño3.4 units, ERSSTv5 (°C)
Oct	+3.64	+3.78	+4.22
Nov	+3.68	+3.78	+4.29
Dec	+3.50	+3.64	+4.08
Jan	+2.96	+3.11	+3.40
Feb	+2.24	+2.41	+2.53
Mar	+1.73	+1.83	+1.89

(b) Where the mechanism test applies if the September offset from the line holds (Niño3.4 anomaly, °C)

Month	Gradient below 0.3 °C, ERSSTv5	Gradient zero, ERSSTv5	Gradient below 0.3 °C, COBE-SST2	Gradient zero, COBE-SST2
Oct	+3.30	+3.59	+3.04	+3.33
Nov	+3.37	+3.66	+3.04	+3.33
Dec	+3.16	+3.45	+2.87	+3.16
Jan	+2.48	+2.77	+2.26	+2.55

(c) Outcomes and their reading

Outcome	Reading
The gradient falls below 0.3 °C in October or November and Niño3.4 is lower in the following month	Consistent with the growth-arrest hypothesis, and the first such case in the growth season: 7 of the 10 earlier months above +1.5 °C in October and November were followed by a rise.
The gradient falls below 0.3 °C only from December and Niño3.4 is lower in the following month	Consistent with the growth-arrest hypothesis but weakly informative: 3 of 7 earlier December months above +1.5 °C rose, and none from January.
The gradient falls below 0.3 °C in any month and Niño3.4 is higher in the following month	The growth-arrest hypothesis is contradicted: the event grew after its gradient was exhausted.
The relative anomaly of any month exceeds the threshold for its calendar month in part (a)	The amplitude test is failed, whatever the gradient.
The gradient stays at or above 0.3 °C and the relative anomaly below the thresholds	Not triggered. The event stopped short of the threshold, as 2015/16 and 2023/24 did, and the question stays open.

Verification quantities: the monthly ERSSTv5 gradient (warm pool, 5°S–5°N, 130°–160°E, minus Niño3, absolute temperatures) and the Niño3.4 and relative anomalies (1991–2020 base), from October 2026 to March 2027, using the values available on 15 May 2027. COBE-SST2 is reported alongside. The September offset is the gradient minus the September line: −0.65 °C in ERSSTv5 and −0.96 °C in COBE-SST2. Part (b) is not a forecast. It says where the mechanism test would apply if the offset held. With the tropical-mean anomaly of September 2026, +0.88 °C, the November threshold of part (a) corresponds to a Niño3.4 anomaly of about +4.56 °C.

Table S13. The main quantities in three SST reconstructions, 1950–2025 (°C; 5–95% ranges from the block bootstrap)

Quantity	ERSSTv5	COBE-SST2	HadISST1
Record used	to September 2026	to September 2026	to July 2026
Slope (°C per °C)	−1.03	−1.05	−1.08
Correlation within months	−0.88	−0.90	−0.90
November threshold	+4.29 (+3.87 to +4.61)	+4.24 (+3.90 to +4.59)	+4.16 (+3.82 to +4.50)
April threshold	+1.76 (+1.56 to +1.94)	+1.70 (+1.53 to +1.87)	+1.65 (+1.48 to +1.81)
November threshold, reduced major axis	+3.75	+3.80	+3.72
November threshold, relative index	+3.47	+3.55	+3.43
95th percentile of the relative threshold, Oct / Nov / Dec / Jan	+3.64 / +3.68 / +3.50 / +2.96	+3.78 / +3.78 / +3.64 / +3.11	+3.62 / +3.64 / +3.39 / +2.95
Months above the ceiling for their month	0	0	0
Closest approach	0.27 below, Mar 2016	0.22 below, Mar 2016	0.18 below, Mar 1983
Months with less than 0.3 °C of gradient, and those followed by a fall	11, 11	7, 7	8, 7
Months above +1.5 °C followed by a rise, January to May	0 of 14	0 of 15	1 of 13
Months above +1.5 °C followed by a rise, September to November	10 of 14	10 of 12	10 of 15
November threshold, 1950–1974 and 2000–2025, and the change	+4.05, +4.71; +0.67 (+0.17 to +1.16)	+3.94, +4.76; +0.82 (+0.35 to +1.26)	+3.82, +4.72; +0.90 (+0.46 to +1.39)
Relative November threshold, 1950–1974 and 2000–2025, and the change	+3.59, +3.57; −0.01 (−0.21 to +0.52)	+3.42, +3.69; +0.27 (−0.02 to +0.75)	+3.26, +3.62; +0.36 (+0.14 to +0.87)
Lowest gradient, 1950–2025	−0.25, Mar 1983	−0.32, Mar 1998	−0.53, Mar 1983
Gradient in the latest month of 2026	0.58	0.56	1.35
Niño3.4 anomaly in the latest month of 2026	+2.86	+2.63	+1.79

HadISST1 uses the same boxes, base period and fits as the other two datasets, with sea-ice points excluded. Root-mean-square differences between the gradients of the datasets in months with Niño3.4 above +1.5 °C in ERSSTv5: ERSSTv5 and COBE-SST2 0.22 °C, ERSSTv5 and HadISST1 0.20 °C, COBE-SST2 and HadISST1 0.25 °C. In HadISST1 the months with less than 0.3 °C of gradient are January to May 1983 and January to March 1998; the one rise, from April to May 1983, is 0.02 °C. Months with a negative gradient since 1950: ERSSTv5 February and March 1983 and March 1998 (lowest −0.25 °C); COBE-SST2 February to April 1983 and January to March 1998 (lowest −0.32 °C); HadISST1 February to May 1983 and February and March 1998 (lowest −0.53 °C). All lay between January and May, and all but one were followed by a fall.

Table S14. The absolute Niño3 temperature at the November threshold, by period (ERSSTv5)

Period	November threshold (°C, Niño3.4 anomaly)	Niño3 SST at the threshold (°C)	Niño3 SST at the threshold minus tropical mean (°C)	Mean November warm-pool SST (°C)
1950–1974	+4.05	28.82	2.17	29.18
1975–1999	+3.71	28.89	1.97	29.41
2000–2025	+4.71	29.50	2.26	29.97
1950–2025	+4.29	29.28	2.33	29.53

The Niño3 SST at the threshold is the 1991–2020 November Niño3 climatology (25.12 °C) plus the Niño3 anomaly that the within-period regression of the Niño3 anomaly on the Niño3.4 anomaly gives at the threshold. It rose by 0.67 °C between the first and last periods, in step with the warm pool, while its value relative to the tropical mean changed by +0.10 °C. A limit set by a fixed absolute temperature, such as a convective thermostat, would not move with the warm pool.

Table S15. Surface zonal wind over 5°S–5°N, 160°E–150°W against the west–east SST gradient in three reanalyses

Reanalysis	Period	Slope (m s ⁻¹ per °C)	r, seasonal cycle removed	Mean wind (m s ⁻¹)	Wind at zero gradient, Oct–Dec (m s ⁻¹)	Wind at zero gradient, Jan–May (m s ⁻¹)	Wind in the months with gradient below 0.3 °C (m s ⁻¹)	Months with westerly monthly-mean wind
NCEP–NCAR R1, sigma 0.995	1950–2025	–0.94	–0.76	–4.2	+0.2 to +0.6	–2.4 to –0.9	–3.0 to –1.1	3: Nov 1982, Oct 1997, Oct 2015
NCEP–DOE R2, 10 m	1979–2025	–0.97	–0.81	–4.2	+0.2 to +0.7	–2.3 to –1.0	–3.2 to –1.2	6: Nov 1982, Aug 1997, Sep 1997, Oct 1997, Nov 1997, Oct 2015
20CRv3, 10 m	1950–2015	–0.99	–0.79	–3.7	+1.1 to +1.6	–2.0 to –0.6	–3.0 to –0.8	8: Nov 1957, Dec 1977, May 1980, Nov 1982, Nov 1991, Dec 1991, Oct 1997, Oct 2015

Reanalysis 2 and 20CRv3 are compared with the ERSSTv5 gradient over their own periods. 20CRv3 assimilates only surface pressure, so its winds are independent of the SST and wind observations that enter Reanalyses 1 and 2. In all three the wind at zero gradient is near zero from October to December and easterly from January to May, the 11 exhausted months were easterly, and every westerly monthly mean occurred with gradient still remaining.

Table S16. Niño3 0–50 m heat-budget terms (NCEP GODAS; K per month, anomalies from the 1980–2025 climatology) in the growth season and in the exhausted months of each event

Event	Months	n	Tendency	Zonal advective feedback	Thermocline feedback	Ekman feedback	Surface flux	Other	Layer gradient	u' (m s ⁻¹)	Q (W m ⁻²)	SST gradient (°C)	Niño3.4 (°C)
1982/83	Jul–Nov growth	5	+0.34	+0.28	+0.34	+0.02	–0.33	+0.06	–0.61	–0.03	33	1.79	+1.48
1982/83	gradient < 0.3 °C	5	–0.25	–0.78	–0.20	–0.69	–0.27	+1.00	–0.11	–0.59	58	0.00	+1.67
1991/92	Jul–Nov growth	5	+0.10	+0.09	+0.13	+0.01	–0.08	–0.04	–0.72	–0.14	53	3.19	+0.96
1991/92	gradient < 0.3 °C	2	–0.25	–0.62	+0.27	–0.79	–0.56	+0.65	–0.18	–0.37	43	0.24	+1.47
1997/98	Jul–Nov growth	5	+0.33	+0.32	+0.41	+0.23	–0.72	+0.33	–0.41	+0.04	3	0.86	+2.25
1997/98	gradient < 0.3 °C	4	–0.86	–0.66	–0.22	–0.30	–0.56	+0.57	–0.08	–0.47	40	0.07	+1.79
2015/16	Jul–Nov growth	5	+0.23	+0.50	+0.31	+0.39	–0.51	–0.07	–0.65	+0.05	20	1.55	+2.31
2025/26	Jul–Sep 2026	3	+0.74	+0.98	+0.52	+0.52	–0.91	+0.06	–0.47	+0.28	–15	0.89	+2.64

Growth season: July–November of the onset year; for 2026, July–September. Exhausted months: ERSSTv5 gradient below 0.3 °C. Other: tendency anomaly minus the two feedbacks and the surface-flux anomaly (meridional advection, the remaining zonal and vertical parts and the residual). Layer gradient: zonal temperature gradient of the 0–50 m layer averaged over Niño3, in K per 1,000 km. u': anomalous zonal current of the layer. Q: net surface heat flux, absolute, in W m⁻². The sum of the two feedbacks in July–September 2026, +1.50 K per month, exceeds the previous three-month maximum of +1.13 K per month (July–September 1997).

Table S17. The paper's fit in CMIP6 historical simulations, 1950–2014 (one member per model; anomalies relative to each simulation's own 1950–2014 climatology)

Model	Slope	r	Nov threshold (°C)	Apr threshold (°C)	Grad Nov (°C)	Max (°C)	Above	Left (°C)	Exhausted Sep–Dec: n / rose
ERSSTv5 (1950–2014)	-1.05	-0.90	+4.37	+1.94	4.57	+2.63	0	-0.87	0 / 0
ACCESS-CM2	-1.03	-0.86	+3.65	+2.33	3.78	+2.74	0	+0.25	0 / 0
ACCESS-ESM1-5	-0.72	-0.74	+5.82	+3.90	4.20	+2.47	0	+0.60	0 / 0
BCC-CSM2-MR	-0.92	-0.84	+5.05	+3.43	4.64	+2.06	0	+0.07	0 / 0
BCC-ESM1	-0.83	-0.87	+4.08	+2.26	3.39	+2.85	0	-0.54	1 / 0
CAMS-CSM1-0	-0.98	-0.90	+3.81	+3.48	3.73	+3.01	0	-0.14	0 / 0
CESM2-FV2	-0.80	-0.84	+5.62	+3.24	4.48	+4.10	1	+0.32	7 / 2
CESM2-WACCM-FV2	-1.02	-0.91	+4.55	+3.10	4.65	+3.38	0	-0.99	1 / 1
CESM2-WACCM	-0.76	-0.84	+7.53	+3.98	5.68	+3.18	0	-0.62	0 / 0
CESM2	-0.96	-0.93	+5.21	+2.77	5.00	+3.36	0	+0.37	0 / 0
CIESM	-0.78	-0.89	+5.65	+2.46	4.38	+3.06	0	-0.13	0 / 0
CMCC-CM2-HR4	-1.02	-0.91	+3.94	+2.58	4.00	+3.07	0	+0.41	3 / 1
CMCC-CM2-SR5	-0.57	-0.78	+9.87	+4.40	5.59	+4.16	0	-0.22	0 / 0
CMCC-ESM2	-0.62	-0.80	+8.52	+4.33	5.31	+3.53	0	-1.08	0 / 0
CNRM-CM6-1-HR	-0.89	-0.80	+4.10	+0.90	3.64	+1.76	0	+0.11	0 / 0
CNRM-CM6-1	-0.91	-0.86	+4.67	+1.11	4.24	+2.52	2	+0.00	0 / 0
CNRM-ESM2-1	-0.80	-0.81	+5.63	+1.03	4.47	+2.27	3	-0.13	0 / 0
CanESM5-CanOE	-0.59	-0.74	+6.62	+3.99	3.90	+2.74	0	-0.07	0 / 0
CanESM5	-0.56	-0.73	+6.92	+4.11	3.91	+3.04	0	-0.39	0 / 0
E3SM-1-0	-0.98	-0.88	+4.51	+1.52	4.41	+3.45	4	-0.15	0 / 0
E3SM-1-1-ECA	-0.86	-0.86	+6.76	+3.25	5.83	+3.64	0	+0.03	0 / 0
E3SM-1-1	-0.97	-0.88	+6.08	+2.98	5.93	+2.76	0	+0.21	0 / 0
EC-Earth3-AerChem	-0.97	-0.88	+4.10	+2.85	3.96	+3.01	0	-0.70	0 / 0
EC-Earth3-CC	-0.91	-0.87	+4.40	+2.47	4.00	+2.81	0	-0.72	0 / 0
EC-Earth3-Veg-LR	-1.04	-0.87	+3.75	+2.35	3.91	+2.57	0	-0.56	1 / 0
EC-Earth3-Veg	-0.98	-0.89	+4.18	+2.41	4.10	+2.96	3	-0.43	0 / 0
EC-Earth3	-1.02	-0.88	+3.97	+2.36	4.06	+2.57	0	-0.51	0 / 0
FGOALS-f3-L	-0.97	-0.96	+3.63	+2.46	3.53	+3.21	5	-0.10	6 / 4
FGOALS-g3	-0.87	-0.92	+3.99	+2.88	3.48	+2.39	0	-0.30	0 / 0
FIO-ESM-2-0	-0.86	-0.88	+5.91	+2.89	5.10	+3.71	0	-0.39	0 / 0
GFDL-CM4	-0.89	-0.89	+6.07	+3.07	5.43	+3.08	0	-0.53	0 / 0
GFDL-ESM4	-0.85	-0.89	+6.43	+3.52	5.49	+3.27	0	+0.33	0 / 0
GISS-E2-1-G-CC	-1.12	-0.92	+1.76	+1.17	1.98	+2.69	51	+0.42	20 / 1
GISS-E2-1-G	-1.10	-0.92	+1.83	+1.17	2.01	+2.86	80	+0.45	34 / 7
GISS-E2-1-H	-1.06	-0.95	+2.68	+2.00	2.84	+2.51	9	-0.42	1 / 0
HadGEM3-GC31-LL	-0.82	-0.88	+5.66	+3.04	4.67	+2.88	0	+0.07	0 / 0
HadGEM3-GC31-MM	-1.14	-0.92	+3.43	+1.70	3.90	+2.19	1	+0.42	0 / 0
IITM-ESM	-0.99	-0.82	+3.35	+0.47	3.33	+2.30	69	+0.01	2 / 0
INM-CM4-8	-0.56	-0.61	+5.51	+2.76	3.08	+1.55	0	-0.21	0 / 0
INM-CM5-0	-0.60	-0.69	+5.73	+2.37	3.42	+1.93	0	-0.23	0 / 0
IPSL-CM5A2-INCA	-0.49	-0.61	+7.73	+7.76	3.77	+2.86	0	-0.42	0 / 0
IPSL-CM6A-LR-INCA	-0.53	-0.66	+10.13	+3.45	5.32	+2.30	0	+0.06	0 / 0
IPSL-CM6A-LR	-0.56	-0.72	+9.42	+3.03	5.24	+4.48	0	-0.88	0 / 0
KACE-1-0-G	-0.80	-0.76	+4.95	+2.26	3.94	+2.37	0	-0.03	0 / 0
MCM-UA-1-0	-0.57	-0.76	+6.84	+3.04	3.88	+2.83	0	+0.04	0 / 0
MIROC-ES2L	-0.87	-0.91	+4.50	+1.27	3.91	+3.93	31	-0.67	3 / 1
MIROC6	-0.77	-0.88	+5.79	+2.47	4.47	+4.20	0	-0.73	0 / 0
MPI-ESM-1-2-HAM	-0.82	-0.79	+6.19	+3.36	5.10	+2.42	0	-0.67	0 / 0
MPI-ESM1-2-HR	-0.90	-0.88	+5.00	+2.93	4.52	+2.22	0	-0.58	0 / 0

Model	Slope	r	Nov threshold (°C)	Apr threshold (°C)	Grad Nov (°C)	Max (°C)	Above	Left (°C)	Exhausted Sep–Dec: n / rose
MPI-ESM1-2-LR	-0.90	-0.85	+4.61	+2.56	4.16	+2.66	0	+0.77	0 / 0
MRI-ESM2-0	-0.98	-0.92	+3.93	+2.98	3.84	+2.74	0	+0.30	0 / 0
NESM3	-0.97	-0.88	+4.25	+2.72	4.11	+2.52	0	-0.47	0 / 0
NorCPM1	-1.06	-0.91	+4.32	+3.16	4.60	+2.48	0	+0.56	0 / 0
NorESM2-LM	-0.82	-0.89	+6.86	+5.14	5.60	+3.67	0	-0.31	0 / 0
NorESM2-MM	-0.81	-0.88	+7.23	+4.50	5.85	+4.40	0	-0.73	0 / 0
SAM0-UNICON	-0.63	-0.72	+8.30	+5.76	5.22	+4.27	0	-1.83	0 / 0
TaiESM1	-1.01	-0.89	+4.86	+2.39	4.90	+3.83	0	-1.26	5 / 2
UKESM1-0-LL	-0.87	-0.86	+5.66	+3.21	4.93	+2.81	0	+0.27	0 / 0

Slope: common slope of the gradient on the Niño3.4 anomaly (°C per °C). r: within-month correlation. Thresholds: Niño3.4 anomaly at which the fitted gradient reaches zero in November and April. Grad Nov: climatological November gradient, 1950–2014. Max: largest monthly Niño3.4 anomaly in 1950–2014. Above: months in which the anomaly exceeded the threshold for its calendar month. Left: gradient remaining at the peak of the largest event, measured from the line for the peak month (negative means less gradient left than the line gives). Models on unstructured grids (AWI-CM-1-1-MR, AWI-ESM-1-1-LR) are excluded. ERSSTv5 is fitted over the same years for comparison; its November threshold over 1950–2025 is +4.29 °C.

Table S18. The growth-arrest test in CMIP6 historical simulations: months with Niño3.4 above +1 °C and less than 0.3 °C of gradient, and whether Niño3.4 rose in the following month, by season, against months with 1–2 °C of gradient left

Criterion	Season	Gradient exhausted: months	rose	%	95% interval	Models	Gradient 1–2 °C: months	rose	%	Without GISS-G and IITM: rose / months (%)
0.3 °C	All months	1873	533	28	26–31%	39	4297	1899	44	322 / 1345 (24%)
0.3 °C	Jan–May	1495	345	23	21–25%	39	2451	697	28	205 / 1131 (18%)
0.3 °C	Jun–Dec	378	188	50	45–55%	17	1846	1202	65	117 / 214 (55%)
0.3 °C	Sep–Dec	201	59	29	23–36%	16	1124	695	62	47 / 109 (43%)
0.3 °C	Oct–Nov	82	17	21	13–31%	11	496	363	73	15 / 37 (41%)
scaled	All months	2050	619	30	28–32%	40	4297	1899	44	381 / 1472 (26%)
scaled	Jan–May	1578	369	23	21–26%	40	2451	697	28	223 / 1204 (19%)
scaled	Jun–Dec	472	250	53	48–57%	18	1846	1202	65	158 / 268 (59%)
scaled	Sep–Dec	249	87	35	29–41%	18	1124	695	62	70 / 141 (50%)
scaled	Oct–Nov	103	32	31	23–41%	12	496	363	73	29 / 53 (55%)
observed	All months	11	0	0						

Months with Niño3.4 anomaly of at least +1 °C in each simulation's own anomalies, 1950–2014, up to three members per model, 145 simulations of 57 models. Scaled: 0.3 °C times the ratio of the simulation's to ERSSTv5's standard deviation of gradient anomalies. Intervals are 95% Wilson intervals. A rise means a higher Niño3.4 anomaly in the following month. The control is months in the same season with 1–2 °C of gradient left. The observed column is ERSSTv5 over 1950–2014. Per-model counts for September–December in the first member are in Table S17.

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