



El Niño-Southern Oscillation Dynamical Response to Volcanic Forcing During the Last Millennium

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Abstract. The El Niño–Southern Oscillation (ENSO) is the dominant mode of interannual climate variability in the global climate system, with widespread impacts on temperature and precipitation. Volcanic eruptions represent one of the most significant external perturbations to the climate system, yet how volcanic forcing influences ENSO remains divided; some studies suggest El Niño-like responses, others La Niña-like responses, or no consistent signal at all. This disagreement may stem from a shared assumption that volcanic forcing acts primarily on ENSO amplitude. This study reframes the question around ENSO’s dynamical evolution, combining Palaeoclimate Modelling Intercomparison Project (PMIP) 3/4 *past1000* climate model simulations and palaeoclimate ENSO reconstructions over the Last Millennium (850 to 1850 CE). Three dynamical diagnostics are assessed: growth and decay rates of Niño3.4 anomalies following eruptions, year-to-year phase transition probabilities, and active-phase duration, conditioned on ENSO phase, eruption seasonality and location. Post-eruption growth and decay rates are predominantly negative across both datasets, with the clearest signal being a suppression of the strong positive growth that normally characterises Neutral phases, suggesting volcanic forcing dampens the development of new active phases. However, this pattern does not reach statistical significance in either dataset. Transition probabilities show a modest, consistent increase in phase persistence across all starting phases, while phase duration remains largely unchanged relative to non-volcanic conditions. Together, these results indicate a state-dependent volcanic influence on ENSO, consistent with transient suppression of the Bjerknes feedback through an atmospheric pathway. This dynamical framing motivates further investigation into whether sustained, clustered volcanism produces longer term shifts in ENSO behaviour.



1 Introduction

The El Niño-Southern Oscillation (ENSO) is a dominant mode of interannual climate variability across the tropical Pacific (Bjerknes, 1969; Philander, 1983) driven by coupled ocean-atmosphere feedbacks, primarily the Bjerknes feedback which links sea surface temperature (SST) anomalies, trade wind strength, and thermocline depth. ENSO oscillates between warm (El Niño) and cool (La Niña) phases on a timescale of two to seven years (Bjerknes, 1969; Zebiak and Cane, 1987; Jin, 1997a, b), with teleconnections that propagate temperature and precipitation anomalies across much of the world (Mason and Goddard, 2001; Lyon and Barnston, 2005; Taschetto et al., 2020). The recharge-discharge oscillator (Jin, 1997a, b) formalises the role of equatorial heat content in driving ENSO phase transitions, with warm water volume buildup during Neutral conditions fuelling the development of El Niño and its subsequent discharge potentially driving the transition toward La Niña (Vialard et al., 2025). ENSO phases typically develop during the austral winter (June, July, August) and peak in austral summer (December, January, February). Understanding how external forcing influences ENSO dynamics, including the timing, transitions, and duration of phase events, is therefore a central problem given the global impacts of ENSO events (Santoso et al., 2017; Liu et al., 2023).

Large explosive volcanic eruptions represent one of the most significant natural external forcing to the climate system (Robock, 2000; Hegerl et al., 2003; Schurer et al., 2013, 2014; Toohey and Sigl, 2017). Through the injection of sulphur dioxide (SO_2) into the stratosphere, major eruptions produce sulphate aerosols that scatter incoming solar radiation, cooling the global surface for one to three years following an eruption (Robock, 2000; Sigl et al., 2015). As ENSO is sustained by tropical Pacific SST gradients and atmospheric circulation, it means that volcanic aerosol forcing constitutes a plausible external modulator of ENSO dynamics.

Most existing literature shows a tendency toward a El Niño-like conditions following large volcanic eruptions (McGregor et al., 2020; Zanchettin et al., 2022; Falster et al., 2023; Dogar et al., 2024), consistent with a broader tendency identified in earlier proxy and model-based work (Adams et al., 2003; Maher et al., 2015; Khodri et al., 2017; Predybaylo et al., 2017, 2020; Pausata et al., 2020, 2023). The mechanisms underlying this El Niño-like tendency are generally interpreted as a dynamical response to differential land-ocean cooling post eruption (Khodri et al., 2017; Pausata et al., 2023). Khodri et al. (2017) identify an indirect pathway in which aerosol-driven cooling of tropical Africa weakens the West African monsoon and generates a Matsuno-Gill response, driving equatorial Kelvin waves and westerly wind bursts over western Pacific. Pausata et al. (2020, 2023) and Fang et al. (2025) further show that ITCZ shifts and extra-tropical teleconnection mediate the response, with the spatial structure of the aerosol forcing determining which pathway dominates, while D'Arrigo et al. (2005) extend the mechanism to ENSO directly, showing that aerosol-driven cooling weakens the Walker Circulation and activates the Bjerknes feedback.

This mechanistic convergence, however, masks substantial variability in outcomes. Predybaylo et al. (2017, 2020) show the response is strongly conditioned by background ocean state and eruption timing, producing a wide range of outcomes under the same forcing, while Fang et al. (2025) show that the pre-eruption ENSO state itself shapes the response for up to five years after an eruption. D'Agostino et al. (2026) identify the central open question as whether the ENSO response is dependent on



pre-eruption ENSO phase. Despite this, pre-eruption ENSO phase has rarely been used as a conditioning variable, with most studies instead compositing eruptions under all ENSO phases.

This study aims to investigate the response of ENSO to volcanic eruptions by examining how volcanic forcing influences ENSO's dynamical evolution, using the pre-eruption ENSO phase as the primary conditioning variable. The Last Millennium saw numerous volcanic eruptions reconstructed from ice-core records, offering an opportunity for investigating how ENSO responds to volcanic forcing across a broad range of eruption season, locations and background climate states (Crowley, 2000; Toohey and Sigl, 2017; Sigl et al., 2022).

Combining PMIP phase 3 and 4 *past1000* model simulations (Jungclaus et al., 2017; Kageyama et al., 2018) and palaeoclimate ENSO reconstructions selected using a principled composite scoring framework (Table S2; (Freund et al., 2025)), we assess three diagnostics of ENSO dynamics over the Last Millennium: the growth and decay rate of Niño3.4 anomalies over the three years following an eruption, year-to-year phase transition probabilities, and the duration of the active ENSO phase at the time of an eruption. Central to this approach is the question of whether the ENSO phase at the time of a volcanic eruption influences the subsequent ENSO response. Drawing on the atmospheric mechanisms identified by Khodri et al. (2017) and Pausata et al. (2020, 2023), and the state-dependent sensitivity documented by Predybaylo et al. (2017, 2020), and the state-dependence explicitly flagged as unresolved by D'Agostino et al. (2026). This study tests the hypotheses that: (i) eruptions occurring during an El Niño phase will suppress or weaken that El Niño phase; (ii) eruptions occurring during a La Niña phase will intensify that La Niña phase; (iii) eruptions occurring during a Neutral ENSO phase will induce a weak El Niño response.

2 Data & Methods

2.1 Climate Model & ENSO Reconstruction Ensemble

Palaeoclimate ENSO reconstructions compiled from Freund et al. (2025) were ranked and selected using a weighted composite score designed to prioritise areas important for the analysis of ENSO dynamical response to volcanic forcing (Table S2). These properties and their weights are as follows: interannual variance preservation ($w = 0.35$), fractional data coverage ($w = 0.30$), temporal variance stability ($w = 0.25$), and within group coherence ($w = 0.10$). Weights were assigned based on the methodological requirements of ENSO volcanic analysis and ENSO reconstruction quality. The list of the selected ENSO reconstructions, their index, archive and proxy season are presented in Table 1. All ENSO reconstructions were used as annual resolution time series using their published seasonal definitions.



Table 1. Selected palaeoclimate ENSO reconstructions

Study	Index	Season	Archive	Region	Method
Freund et al. (2019) Niño4 DJF	Niño4	Dec–Feb	Corals	Trop. Pac., Indian Ocean	PCR
Zhu et al. (2022) Li13b6	Niño3.4	Dec–Feb	Corals	Pacific, Atlantic	Regression
Wilson et al. (2010) Niño3.4 COAPCR	Niño3.4	Dec–Nov	Multi-proxy	Pacific Basin	RegEM / PCR
Li et al. (2011) NADA PC1	Niño3	Jan–Mar	Tree-rings	SW North America	EOF/PCA
D’Arrigo et al. (2005) Niño3	Niño3	Dec–Feb	Tree-rings	subtropical North America	PCR
Stahle and Cleaveland (1993)	SOI	Oct–Mar	Tree-rings	USW, Mexico	Regression
Liu et al. (2024) PCR	Niño3.4	Dec–Feb	Multi-proxy	Near-global	PCR
Dätwyler et al. (2020) ENSO DJF	Niño3.4	Dec–Feb	Multi-proxy	Near-global	PCR
Emile-Geay et al. (2013) Niño3.4	Niño3.4	Dec–Feb	Multi-proxy	Near-global	RegEM

PCR = principal component regression; RegEM = regularised expectation maximisation; COAPCR = combined ocean–atmosphere PCR.

Climate model data was obtained from PMIP3 and PMIP4 *past1000* experiments ((Jungclaus et al., 2017); Table 2). The use of a multi-model ensemble allows the ENSO dynamical response to volcanic eruptions to be assessed across differing representations of tropical Pacific variability. Monthly surface temperature data (*ts*) were used to characterise tropical Pacific SST variability. Prior to analysis, each model was regridded onto a common 1.5 x 1.5 degree longitude-latitude grid.



Table 2. Climate models used in this study.

Model Name	PMIP Phase	
<i>PMIP4</i>		
MIROC-ES2L	PMIP4	Hajima et al. (2020)
MPI-ESM1-2	PMIP4	Mauritsen et al. (2019)
MRI-ESM2-0	PMIP4	Yukimo et al. (2019)
<i>PMIP3</i>		
BCC-ESM1-1	PMIP3	Wu et al. (2020)
CCSM4	PMIP3	Gent et al. (2011)
CSIRO-Mk3L-1-1	PMIP3	Phipps et al. (2011)
GISS-E2-R	PMIP3	Schmidt et al. (2014)
IPSL-CM5A-LR	PMIP3	Dufresne et al. (2013)
MIROC-ESM	PMIP3	Watanabe et al. (2011)
MPI-ESM-P	PMIP3	Giorgetta et al. (2013)

Volcanic eruption years were identified using the eVolv2k_version4 volcanic forcing reconstruction derived from ice-core records from Greenland and Antarctica (Sigl and Toohey, 2024). Only eruptions with confirmed seasonality and location were considered for this study, a full list of the selected volcanic eruptions is provided in Table S1. Volcanic eruptions were not grouped or selected based on eruption strength as this selection is less useful for the Last Millennium, given the focus on combinations of ENSO and volcanic eruptions, this was done to retain the largest possible sample size. Large ensemble based studies, such as those in Fang et al. (2025), are better placed to investigate these selection questions. For the first analysis, eruptions were grouped all together, then, in the second analysis, eruptions were grouped by seasonality, and in the third analysis, the eruptions were grouped by location.

2.2 ENSO Index

Monthly SST fields from climate models were used to create a relative Niño3.4 index. First, SST anomalies were calculated for each month by subtracting the model's average climatology across the analysis period (850-1849 CE). The regional mean anomaly for the Niño3.4 area (5°S - 5°N to 190°E - 240°E) was then calculated and subtracted from the mean tropical SST anomaly. A three-month running mean, centred on each month, was then applied to produce the relative Niño3.4 index. Palaeoclimate reconstructions were handled using their originally published methods and seasonal definitions. ENSO phase was classified during austral summer using a threshold of ± 0.5 degree Celsius for the temperature based reconstructions.



2.3 Growth & Decay Rate

To quantify post-eruption amplitude evolution of Niño3.4 anomalies, an exponential growth and decay rate metric was applied to eruption-aligned ENSO composites. For each dataset, composites $C_E(t)$ were constructed by averaging ENSO anomalies across all events within a ± 5 -year eruption window. Four variants were evaluated: an unconditional case using all eruptions, and three conditioned cases grouping eruptions by eruption location, by seasonality, and by background ENSO phase (El Niño, Neutral, La Niña).

Rates were estimated over lags $t = 0$ to $+3$ years by fitting:

$$C_E(t) \approx C_0 + Ae^{(rt)} \quad (1)$$

where $r(\text{yr}^{-1})$ is the growth and decay rate. A is an amplitude coefficient, and C_0 is a background offset estimated as the median of the final two composite values in the fitting window. The rate r was obtained using linear regression of $\log|C_E(t) - C_0| = \alpha + rt$ against t . Positive r indicates post-eruption amplification; negative r indicates decay, with e-folding timescale $\tau = -\frac{1}{r}$.

Statistical significance was assessed using Monte Carlo resampling. Control composites were drawn from eruption-free periods of the same time series, matching the eruption sample size (and ENSO phase composition in the conditional case), yielding a null distribution against which two-sided p-values were computed. Climate models and palaeoclimate reconstructions were treated as separate groups throughout, with per-dataset rates summarised by the median and interquartile range (IQR) across datasets within each group.

2.4 Transition Probability

To assess whether volcanic eruptions influence year-to-year ENSO evolution, phase-conditioned transition probabilities were estimated for eruption years and compared against a non-volcanic baseline. Phase transitions were defined as ordered phase pairs ($\text{phase}_y \rightarrow \text{phase}_{y+1}$), with eruption-year transitions originating in volcanic eruption years and baseline transitions drawn from eruption-free periods of the same time series.

For each dataset and starting phase $s \in (\text{El Niño}, \text{Neutral}, \text{La Niña})$, counts of subsequent-year outcomes $k \in (\text{El Niño}, \text{Neutral}, \text{La Niña})$ were tabulated and normalised to yield conditional transition distributions $p_E(k|s)$ and $p_B(k|s)$. This conditional formulation isolates changes in ENSO evolution given background state, rather than conflating transition behaviour with phase frequency shifts.

Probabilities were pooled across datasets using equal-weight linear pooling (Geweke and Amisano, 2011), averaging distributions only over contributing datasets. Results are presented separately for climate models and palaeoclimate ENSO reconstructions, with volcanic transition probabilities compared directly against the baseline for each starting phase. Statistical significance was assessed via permutation testing.



2.5 Phase Persistence

To quantify whether volcanic eruptions influence ENSO phase persistence, the remaining lifetime of the current phase was evaluated following each eruption. From each annual ENSO phase time series, contiguous sequences of identical phase labels were identified. For a phase beginning at year y_0 and ending at y_1 , the remaining lifetime at year y is:

$$L(y) = y_1 - y + 1 \quad (2)$$

Persistence was evaluated at offsets $t = +1, \dots, +5$ years following each eruption. For a given eruption year e and offset t , an anchor year $a = e + t$ was defined, retaining only anchors where the dataset was in phase s . The eruption-sample diagnostic was the mean remaining lifetime $L_E(s, t)$ across valid years. A phase-matched null distribution was constructed using Monte Carlo resampling (6,000 iterations), and volcanic effects were expressed as anomalies relative to the null median:

$$\Delta L(s, t) = L_E(s, t) - \text{median} L_B(s, t) \quad (3)$$

Two-sided p-values were computed by comparing observed deviations against the null distribution, with statistically significant anomalies ($p < 0.05$) indicated by hatching in the results. Climate models and palaeoclimate ENSO reconstructions were summarised separately, with per-dataset values pooled by taking the median across datasets within each group.

2.6 Season and Location-Conditioned Analyses

The growth and decay rate, transition probability, and phase persistence diagnostics described in Sections 2.3–2.5 were additionally applied using two alternative eruption groupings: eruption season and eruption location. These analyses follow an identical methodology to the phase-conditioned case; the only difference is the criterion used to subset eruptions before compositing. For the season-conditioned analysis (Section 3.2), eruptions were grouped by the season of eruption onset (DJF, MAM, JJA, SON) rather than by pre-eruption ENSO phase. For the location-conditioned analysis (Section 3.3), eruptions were grouped by source latitude into tropical ($23.5^\circ\text{S} - 23.5^\circ\text{N}$) and Northern Hemisphere extratropical ($>23.5^\circ\text{N}$) categories, following the eruption latitude classification in Table S1. In both cases, all methods are performed exactly as described in Sections 2.3–2.4.



3 Results

3.1 ENSO Response to all Eruptions

150 Growth and decay rates of Niño3.4 anomalies following volcanic eruptions across PMIP last millennium simulations and ENSO reconstruction ensemble are shown in Fig. 1. Across both datasets, post-eruption growth and decay rates are predominantly negative, indicating that ENSO anomalies tend to decay more rapidly in the years following an eruption than under unforced conditions. This behaviour is consistent across all ENSO phase groupings. Eruptions occurring during El Niño and La Niña conditions are associated with weakening growth and decay rates in both models and reconstructions. Neutral conditions yield
 155 rates closer to zero, though the spread across individual members remains large; individual model growth and decay rates span -1.50 to 1.74 yr^{-1} , and reconstruction growth and decay rates span -1.41 to 0.50 yr^{-1} , driven primarily by Neutral phase variability for models (IQR = 0.91 yr^{-1}). Broad directional agreement of the growth and decay rate signal is observed between models and reconstructions across all phase groupings.

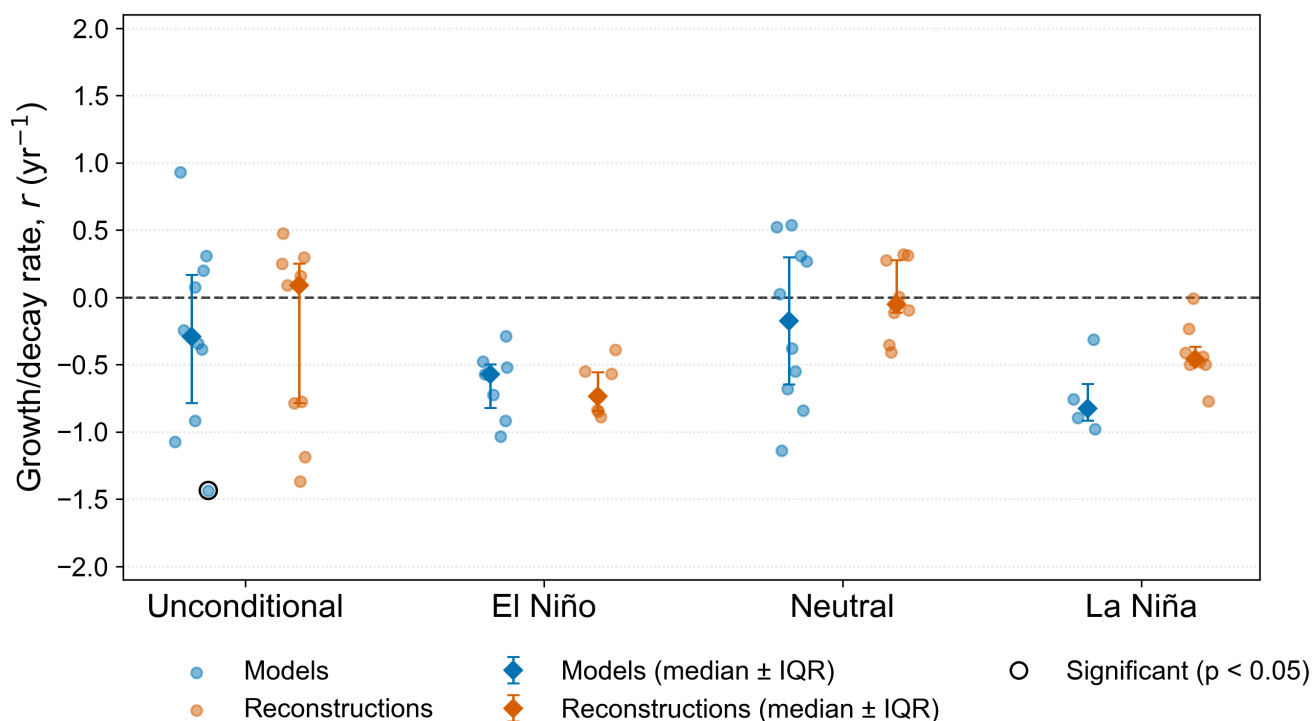


Figure 1. Growth and decay rates (r (yr^{-1})) of ENSO events following volcanic eruptions, conditioned on the initial ENSO state (Unconditional, El Niño, Neutral, La Niña). Blue and orange circles show individual PMIP simulations and palaeoclimate ENSO reconstruction, respectively, with filled diamonds indicating the ensemble median $\pm$ interquartile range. The dashed horizontal line denotes $r = 0$, representing no change from non-volcanic baseline. Circled markers indicate values statistically significant at $p < 0.05$ level.



ENSO phase transition probabilities following volcanic eruptions are shown in Fig. 2 for the PMIP model ensemble (a) and palaeoclimate ENSO reconstructions (b), with inner rings representing volcanic and outer rings representing non-volcanic baseline probabilities. Across both datasets and all ENSO phase groupings, differences between volcanic and baseline transition probabilities are generally small, with no grouping producing a large or systematic shift in phase preference following an eruption. Most groups show slight increases in phase persistence, with the most pronounced changes occurring in transitions out of an El Niño state; persistence increases from 19% to 28% in models (Fig. 2a) and from 36% to 45% in reconstructions (Fig. 2b). Notable differences between the two datasets are apparent in the proportion of transitions toward a Neutral phase. Models exhibit a substantially higher probability of transitioning to Neutral across all initial phases, with this probability not falling below 46% and, compared to a range of 35 - 42% in reconstructions (Fig. 2). Statistical significance for each phase transition within the individual climate models and palaeoclimate ENSO reconstructions is presented in Table S3.

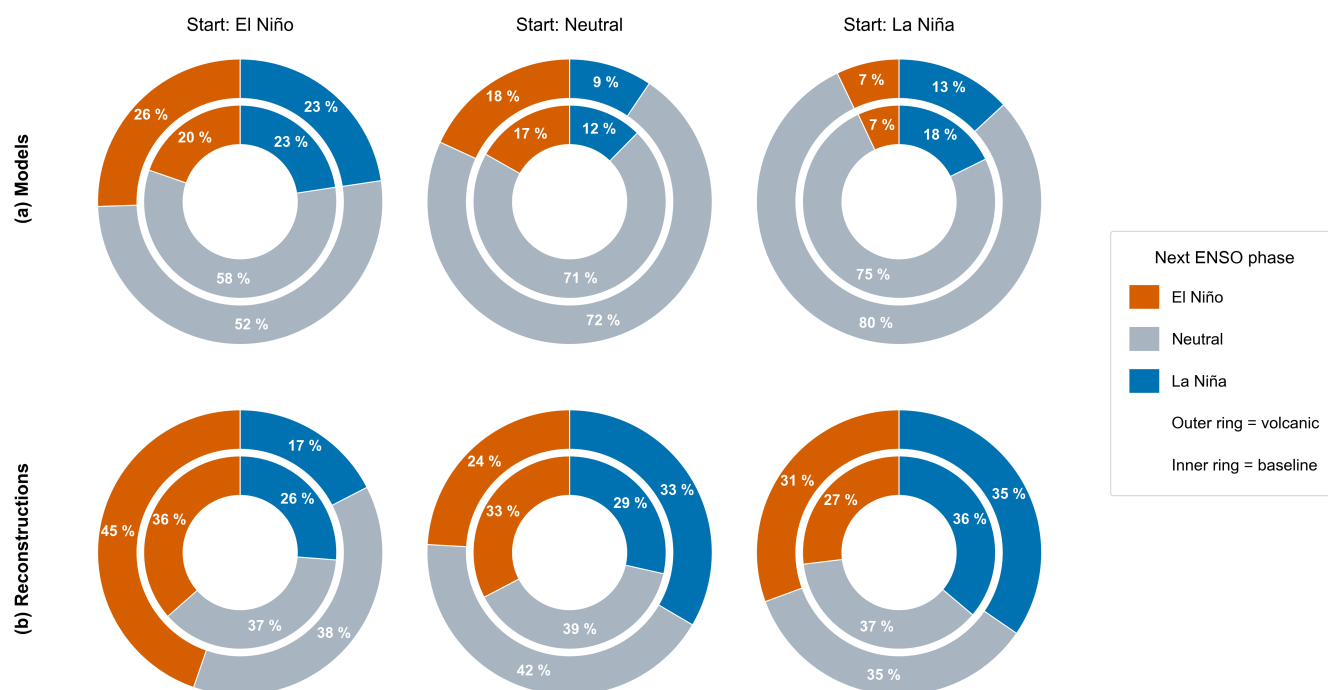


Figure 2. Year-to-year ENSO phase transition probabilities following volcanic eruptions, conditioned on the ENSO state at the time of eruption (El Niño, Neutral, La Niña), for the PMIP last millennium simulations (a) and palaeoclimate ENSO reconstructions (b). Each doughnut chart shows the probability of transitioning to El Niño (orange), Neutral (grey), or La Niña (blue) in the year following an eruption. The outer ring shows transition probabilities during volcanic years, and the inner ring shows baseline (non-volcanic) transition probabilities.

Phase duration following volcanic eruptions is largely unchanged relative to the control period across all ENSO states, in both model simulations and ENSO reconstructions (Fig. 3). In the Neutral, El Niño, and La Niña phases, the median phase duration sits at one year, consistent with the control median, with the vast majority of eruptions clustering tightly on the median.



The concentration of events indicates that volcanic forcing does not systematically prolong or shorten ENSO phase duration, regardless of the background climate state at the time of eruption.

While a small number of outliers extend to longer durations, reaching up to eight years in the Neutral phase for models, and four years in the El Niño and La Niña phases for both models and reconstructions, these are isolated cases. This could be due to the influence of model initial conditions on ENSO responses identified by Fang et al. (2025). In both models and reconstructions, the medians fall within the control median in all three phases, and the bulk of the distribution remains well within the control IQR. Together, these results suggest that volcanic eruptions have little to no consistent influence on how long a given ENSO event persists following an eruption, suggesting that any apparent multi-year responses are likely dominated by internal variability.

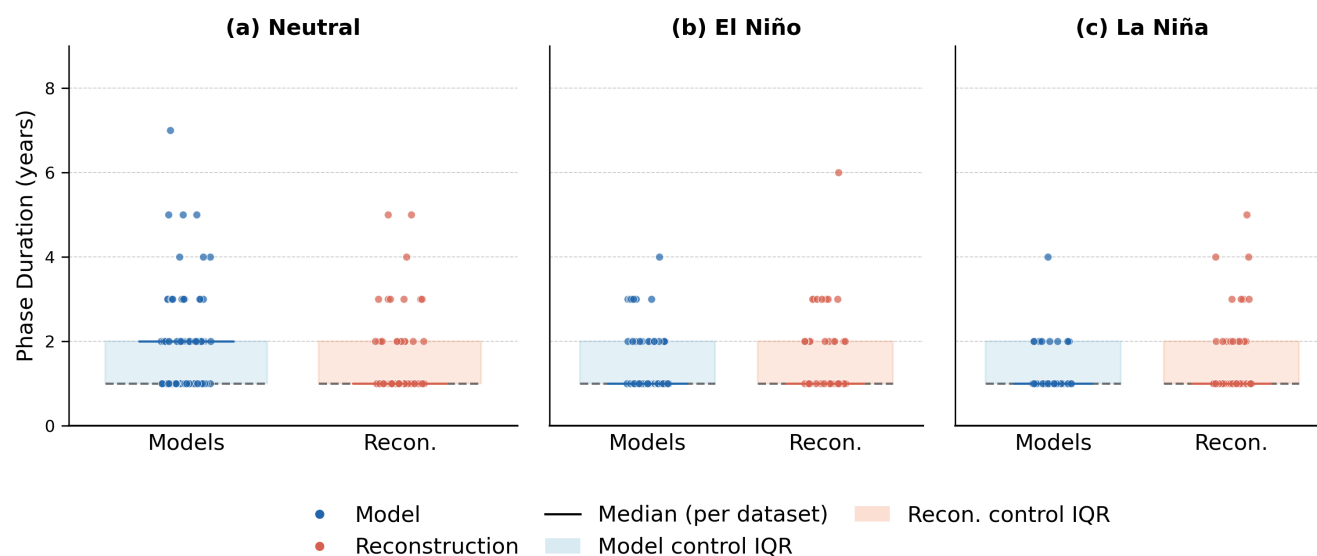


Figure 3. ENSO phase duration following volcanic eruptions, conditioned on the ENSO state at the time of an eruption (Neutral, El Niño, La Niña), for PMIP simulations (blue), palaeoclimate ENSO reconstructions (orange). Individual eruptions are shown as points, with the median of each distribution indicated by the horizontal black bar. The dashed blue line and shaded band denote the median and interquartile range of the control distribution.

3.2 ENSO Response Conditional on Eruption Season

We have shown above that volcanic eruptions have little impact on the ENSO phase persistency. Next, we investigate if eruption seasonality might explain this. We find that eruption season alters the growth and decay rate results, with differences particularly apparent between austral summer (DJF) and austral winter (JJA) (Fig. 4a & b). Eruption seasonality plays an important role in the growth and decay rate signal of active ENSO events, with DJF and MAM eruptions producing more negative rates than eruptions occurring in JJA or SON. There is a difference between the months when ENSO events are developing and when ENSO events are at their peak or decaying. The signal between the ENSO's developing months of JJA and SON (Fig. 4c & d)



is similar, with El Niño and La Niña events showing negative growth and decay rates in both seasons and comparatively little seasonal spread relative to the DJF and MAM groupings. The clearest seasonal signal emerges in the SON panel (Fig. 4d), where two model realisations in the Neutral category return strongly negative, statistically significant growth and decay rates in contrast to the near-zero or positive Neutral rates seen at other eruption seasons.

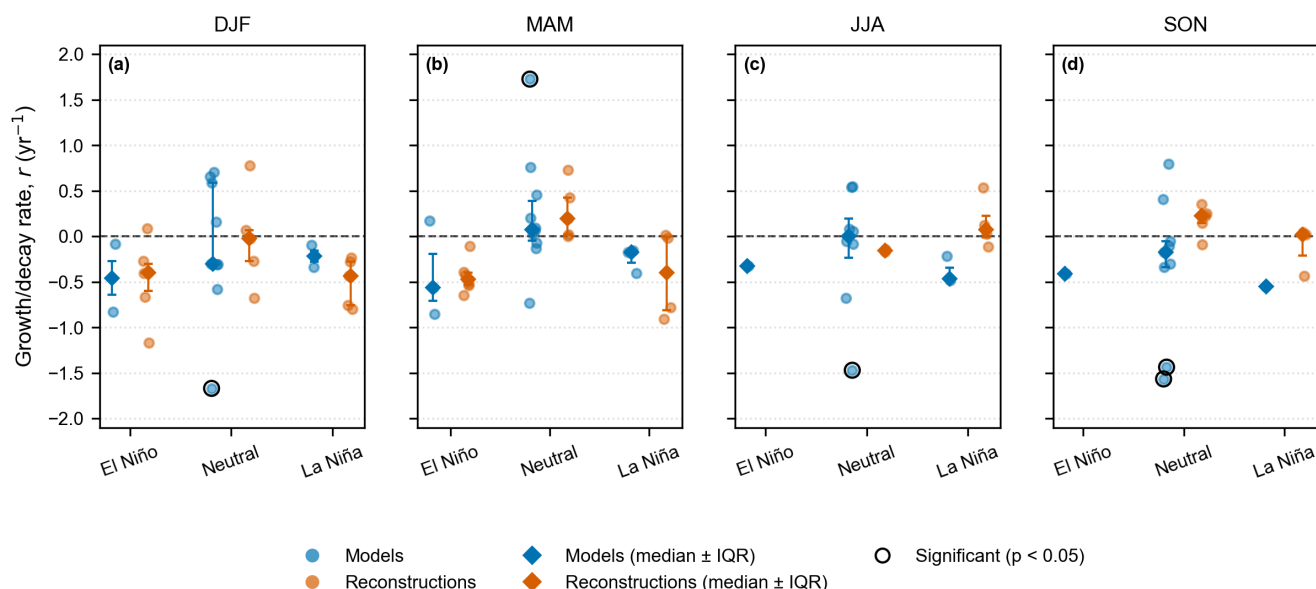


Figure 4. Growth and decay rates ($r(\text{yr}^{-1})$) of ENSO events following volcanic eruptions, conditioned on eruption season (DJF, MAM, JJA, SON) and initial ENSO state (El Niño, Neutral, La Niña). Blue and orange circles show individual PMIP simulations and palaeoclimate ENSO reconstructions, respectively, with filled diamonds indicating the ensemble median $\pm$ interquartile range. The dashed horizontal line denotes $r = 0$, representing no change from observed growth and decay rates. Circled markers indicate values statistically significant at $p < 0.05$. Note no El Niño events were identified in JJA or SON across the model ensemble

ENSO transition probabilities conditioned on eruption season (Fig. 5) reveal a distinction between eruptions occurring during the growth phase of ENSO (JJA, SON), when anomalies are strengthening toward their austral summer peak, and eruptions occurring during the peak phase of ENSO (DJF, MAM). For eruptions during the peak phase, the dominant effect is a reduction of the active phase toward Neutral, DJF eruptions during La Niña, for example, push models from a 76% baseline probability of transitioning to Neutral up to 100% following an eruption, effectively eliminating La Niña persistence. By contrast, eruptions during ENSO's growth phase show a tendency to reinforce the active phase. JJA eruptions during El Niño increase persistence in models from a 15% baseline to 33% following an eruption, with a corresponding fall in the probability of transitioning to Neutral (57% baseline to 28% following an eruption). Reconstructions show a broadly similar seasonal asymmetry, with El Niño persistence following JJA eruptions elevated above its baseline, though the magnitude of the shift differs from the model ensemble.

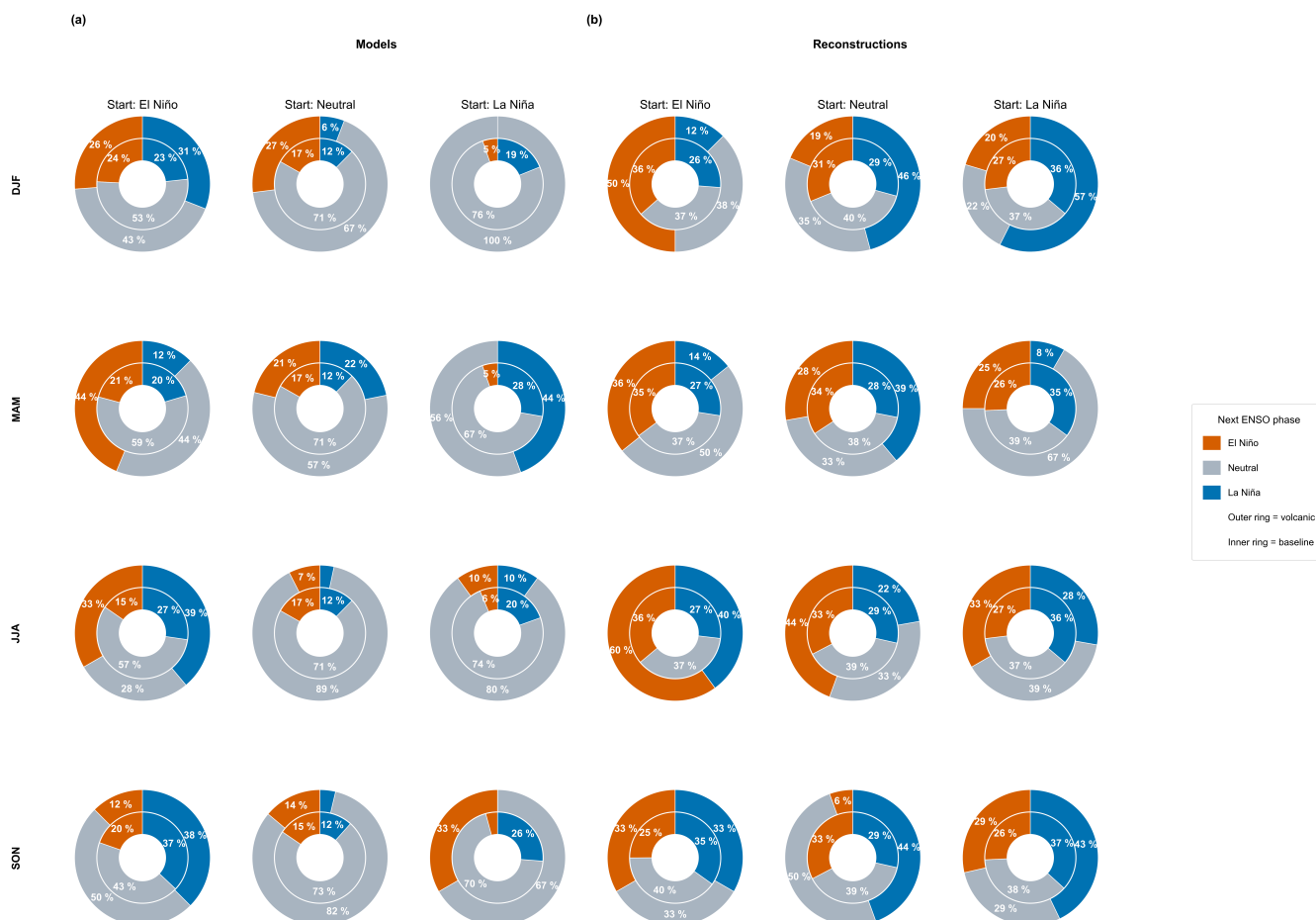


Figure 5. Year-to-year ENSO phase transition probabilities following volcanic eruptions, conditioned on eruption season (DJF, MAM, JJA, SON) and initial ENSO state (El Niño, Neutral, La Niña), for (a) models and (b) reconstructions. Inner rings show baseline (non-volcanic) transition probabilities; outer rings show transition probabilities in years following a volcanic eruption. Segment colour denotes the ENSO phase transitioned to (El Niño, Neutral, La Niña), with percentages indicating the proportion of transitions to each phase.

ENSO phase duration conditioned on eruption season (Fig. 6) mirrors the results in Fig. 3. Medians for both models and reconstructions remain at or close to one year across all four seasons and all three ENSO phases, with the bulk of the distribution falling within the non-volcanic control IQR. The longest-duration outliers appear predominantly in the DJF and MAM model distributions (Neutral phase reaching up to seven years in MAM, six years in DJF) rather than being evenly spread across seasons, though given the small sample size of eruptions with known seasonality this should be treated as suggestive rather than conclusive.

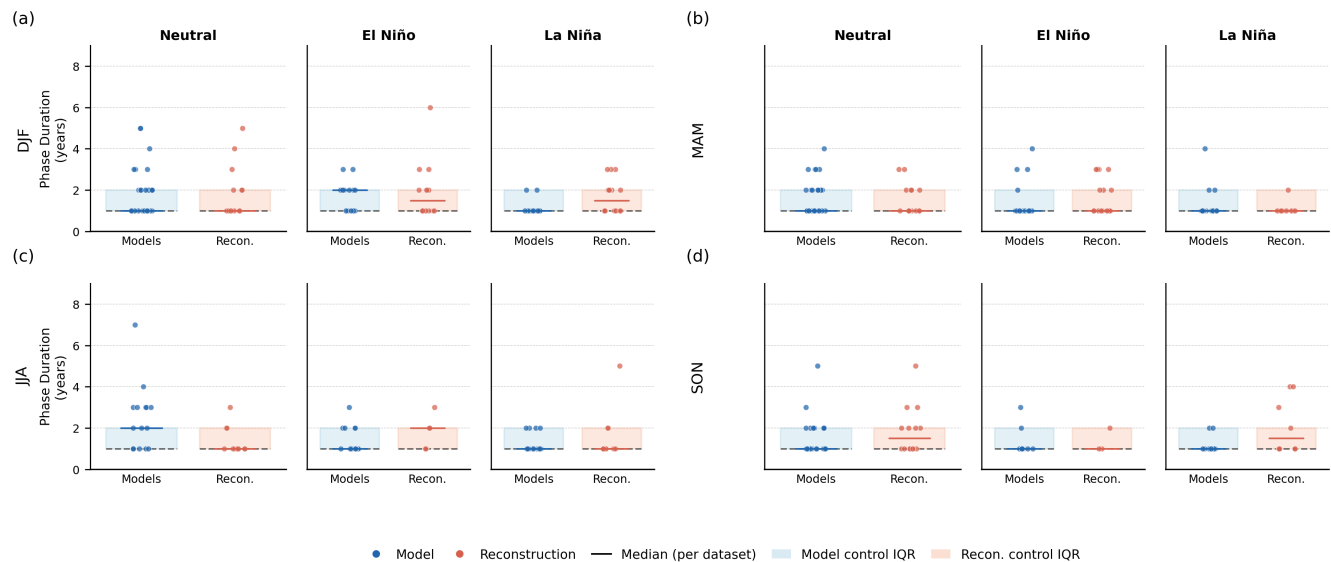


Figure 6. ENSO phase duration following volcanic eruptions, conditioned on eruption season for (a) DJF, (b) MAM, (c) JJA, (d) SON and the ENSO state at the time of an eruption (Neutral, El Niño, La Niña), for PMIP simulations (blue) and palaeoclimate ENSO reconstructions (orange). Individual eruptions are shown as points, with the median of each distribution indicated by the horizontal bar. The dashed line and shaded bands denote the median and interquartile range of the control distribution for models (blue) and reconstructions (orange), respectively.

3.3 ENSO Response Conditional on Eruption Location

Growth and decay rates conditioned on eruption location (Fig. 7) differ substantially between tropical and Northern Hemisphere (NH) extratropical eruptions. For tropical eruptions (Fig. 7a), El Niño-phase rates are consistently negative and comparatively tightly clustered across both models and reconstructions, with one reconstruction value statistically significant at approximately -1.75 yr^{-1} . Neutral-phase rates following tropical eruptions are more positive than in the phase-conditional case, with one model (1.2 yr^{-1}) and one reconstruction (1.9 yr^{-1}) both reaching statistical significance, the opposite sign to the Neutral-phase suppression identified in Fig. 1. La Niña rates following tropical eruptions remain negative but show less spread than the El Niño or Neutral groupings.

NH extratropical eruptions (Fig. 7b) produce a different pattern. El Niño phase rates are negative and tightly clustered around a similar magnitude to the tropical case, with one reconstruction significant at a comparable level (-1.6 yr^{-1}). Neutral phase rates following NH extratropical eruptions span both positive and negative values with wide spread and no significant grouping, in contrast to the strongly positive tropical Neutral signal. La Niña rates show the largest divergence between the two eruption locations, NH extratropical eruptions produce the single most negative and most significant value in the dataset (-2.0 yr^{-1} , models), while tropical eruption rates are comparatively modest.

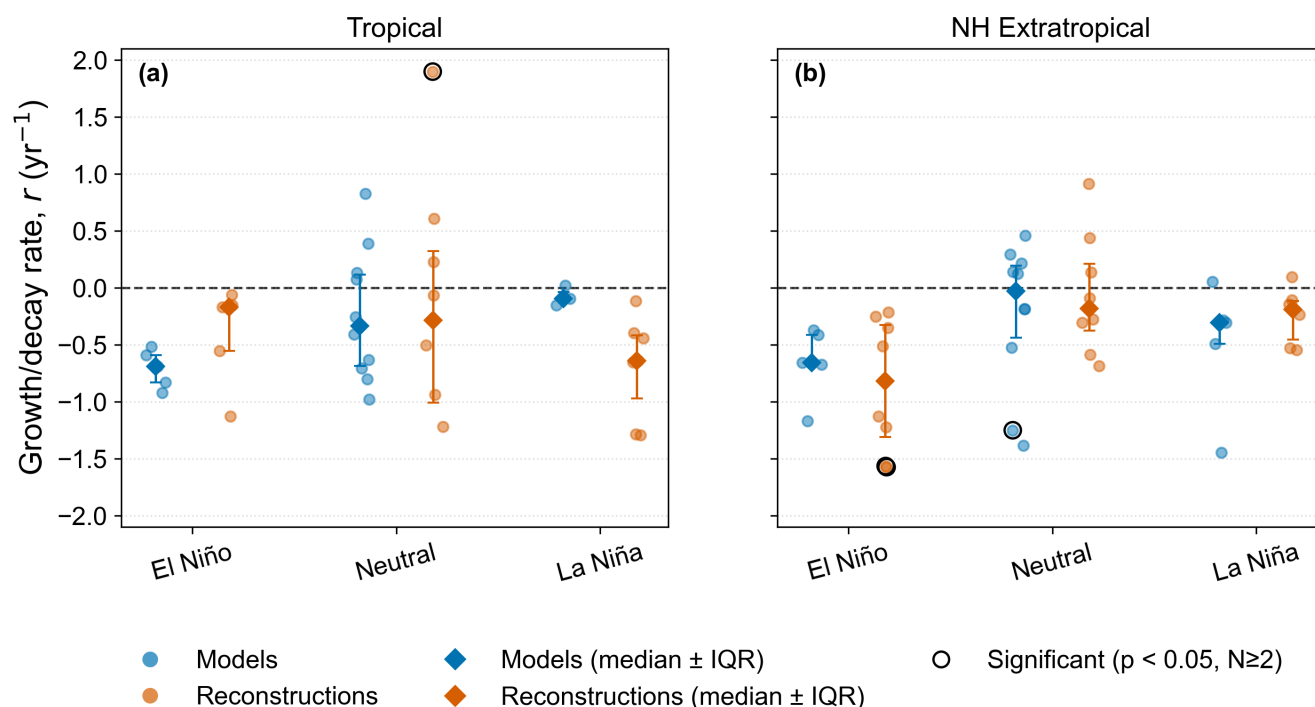


Figure 7. Growth and decay rates ($r(\text{yr}^{-1})$) of ENSO events following volcanic eruptions, conditioned on eruption location ((a) Tropical, (b) Northern Hemisphere Extratropical) and initial ENSO state (El Niño, Neutral, La Niña). Blue and orange circles show individual PMIP simulations and palaeoclimate ENSO reconstructions, respectively, with filled diamonds indicating the ensemble median $\pm$ interquartile range. The dashed horizontal line denotes $r = 0$, representing no change from the non-eruption case. Circled markers indicate values statistically significant at $p < 0.05$.

Transition probabilities conditioned on eruption location (Fig. 8) show that persistence increases following eruptions in both initial El Niño and La Niña phases at both eruption locations, broadly consistent with the phase-conditioned result in Fig. 2. For tropical eruptions, El Niño persistence increases from 20% (baseline) to 32% (volcanic) in models and from a comparable increase in reconstructions, while the probability of transitioning to Neutral from an El Niño start falls from 59% to 50% in models. Starting from Neutral, the probability of remaining in a Neutral phase is high in both datasets (models: 72% baseline to 64% volcanic, reconstructions: 39% baseline to 48% volcanic), with El Niño transition probability increasing from 16% to 27% in models following tropical eruptions. For NH extratropical eruptions, the pattern is directionally similar, but the magnitude of the shift differs by starting phase, most notably for La Niña, models show persistence rising from 16% to 23% (with the corresponding Neutral transition probability falling from 78%), a shift the tropical La Niña grouping does not reproduce as strongly.

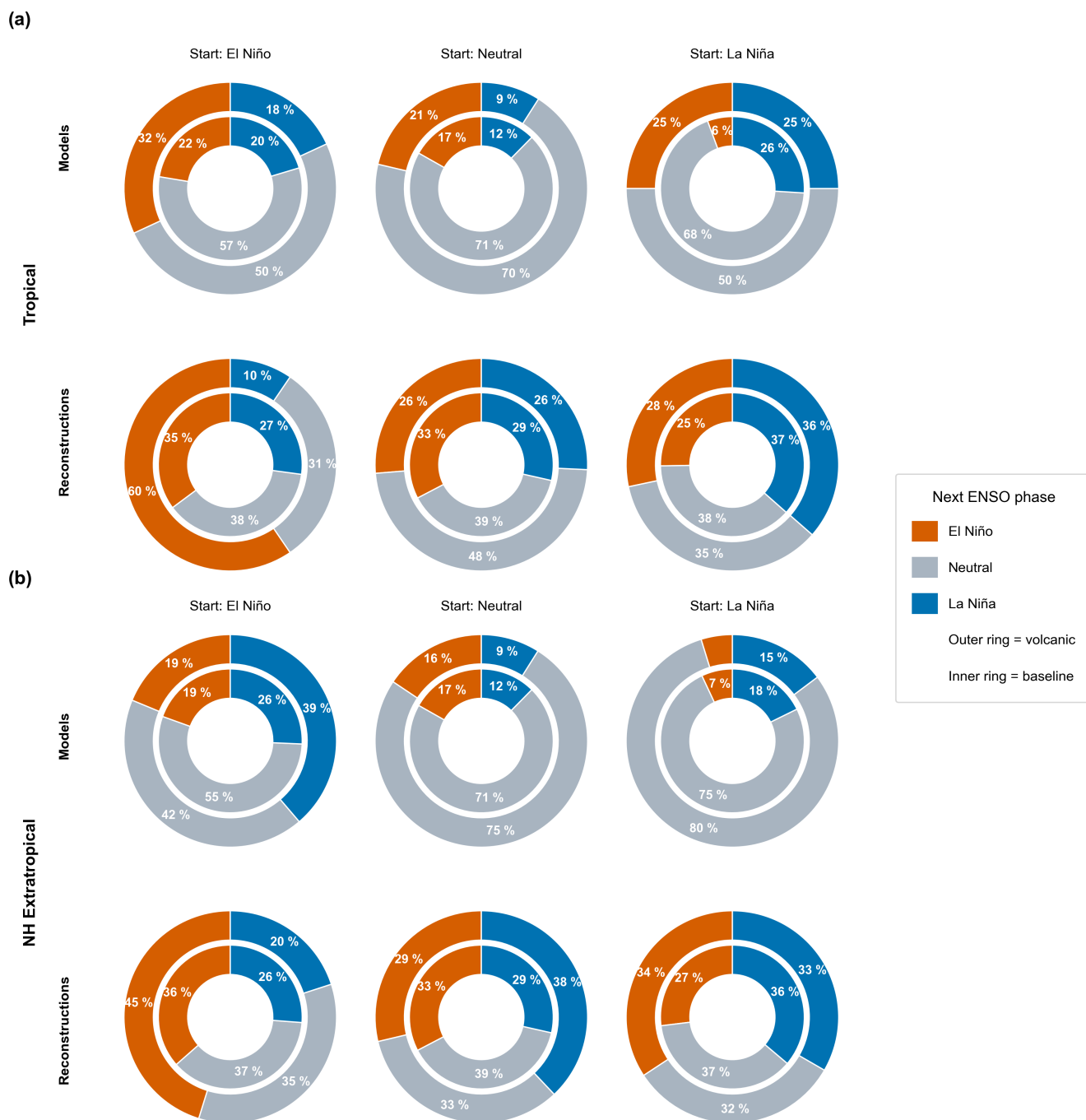


Figure 8. Year-to-year ENSO phase transition probabilities following volcanic eruptions, conditioned on eruption location (Tropical, Northern Hemisphere Extratropical) and the ENSO state at the time of eruption (El Niño, Neutral, La Niña), for PMIP simulations and palaeoclimate ENSO reconstructions. Each doughnut chart shows the probability of transitioning to El Niño (orange), Neutral (grey), or La Niña (blue) in the year following an eruption. The outer ring shows transition probabilities during volcanic years and the inner ring shows baseline (non-volcanic) transition probabilities.



Phase duration conditioned on eruption location (Fig. 9) shows the same pattern established in the seasonal case, median durations sit at or close to one year across all three phases and eruption locations, with the bulk of eruptions clustering at the control median in both models and reconstructions. This result holds regardless of whether the eruption occurred in the tropics or the NH extra-tropics, suggesting that eruption location does not systematically extend or shorten the duration of the active ENSO phase at the time of eruption.

As in the phase-conditioned and seasonal results, the clearest departures from this pattern occur in the Neutral phase, and here eruption location does not modulate the extent of the upper tail. NH extratropical eruptions during Neutral conditions produce the longest individual outliers in the model ensemble, reaching eight years. Reconstructions show a comparatively narrow upper tail at both locations, reaching at most five years for tropical eruptions and three years for NH extratropical eruptions. El Niño and La Niña phase durations show a tighter distribution across both locations, with outliers rarely exceeding three to four years, the exception being one reconstruction value of six years following a tropical eruption during El Niño conditions. The NH extratropical La Niña (Fig. 9b) grouping shows the widest spread, with one model realisation reaching four years and one reconstruction reaching five years, though the median in both datasets remains anchored at the control value.

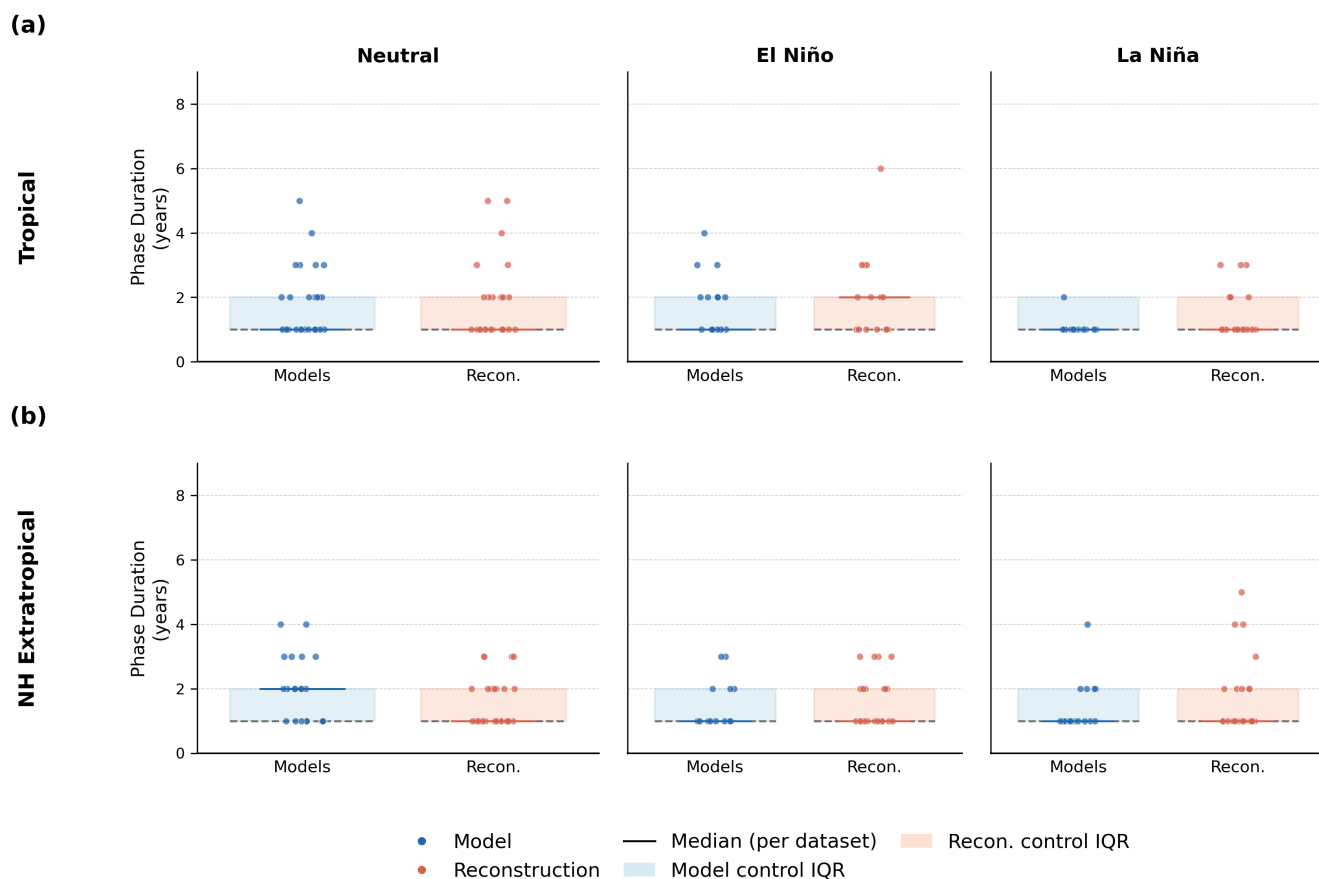


Figure 9. ENSO phase duration following volcanic eruptions, conditioned on eruption location ((a) Tropical, (b) Northern Hemisphere Extratropical) and the ENSO state at the time of an eruption (Neutral, El Niño, La Niña), for PMIP simulations (blue) and palaeoclimate ENSO reconstructions (orange). Individual eruptions are shown as points, with the median of each distribution indicated by the horizontal bar. The dashed line and shaded bands denote the median and interquartile range of the control distribution for models (blue) and reconstructions (orange), respectively.

4 Discussion

Across both model and reconstruction datasets, growth and decay rates of Niño3.4 anomalies are negative, with median rates below zero for the El Niño and La Niña phase groupings. Relative to an observational baseline (Fig. S1), which retains the strong positive Neutral growth rate and pronounced active phase decay characteristic of unforced ENSO variability, post-eruption rates are suppressed toward zero values in both models and reconstructions, indicating a dampening of the phase-dependent growth rate structure. The wide spread of growth and decay rates (models: -1.50 to 1.74 yr^{-1} ; reconstructions: -1.41 to 0.50 yr^{-1}) is consistent with the well-documented sensitivity of post-eruption ENSO response to ocean pre-conditioning and eruption timing (Lehner et al., 2016; Predybaylo et al., 2020). Conditioning on eruption season and location shows this sensitivity is



not simply noise around a single dampened response but it resolves into sub-signals that the phase-conditional result averages
 255 over. It should be noted, however, that the majority of growth and decay rates do not reach statistical significance; the patterns
 are therefore best interpreted as tendencies.

The dampening result is consistent with the atmospheric teleconnection pathway described by Khodri et al. (2017), in which
 aerosol-driven cooling weakens La Niñas anomalous upwelling and sustains El Niño events rather than producing a discrete
 amplitude shift, a characterisation that maps onto the accelerated decay identified here. The dominance of this pathway over
 260 the ocean dynamical thermostat is further supported by Pausata et al. (2020) and Pausata et al. (2023), and synthesised by
 D’Agostino et al. (2026). These studies identify eruption latitude as a key control on which mechanism, tropical land cooling,
 ITCZ displacement, or extratropical teleconnection, dominates the response for a given eruption. The season and location
 conditioned results below are interpreted in this context.

Once conditioned by eruption seasonality, the results reveal two opposing tendencies underlying the pooled dampening
 265 signal. Eruptions during the peak months of ENSO (DJF, MAM) are associated with a collapse of the active phase toward
 Neutral conditions, DJF eruptions during La Niña push, for example, modelled phase transitions from a 76% baseline up to
 100%. Eruptions during the developing months (JJA, SON) instead reinforce the active phase. JJA eruptions during El Niño
 increase in the model phase persistence from a 15% baseline to 33%, with reconstructions showing broadly similar asymmetry.
 This timing-dependence is consistent with the seasonally-gated nature of the Khodri et al. (2017) pathway, which operates
 270 through the boreal-summer West African monsoon. This is broadly consistent with Fang et al. (2025), who show in an idealised
 ensemble (their Fig. 11) that northern extratropical eruptions beginning in an El Niño state have a $> 70\%$ chance of a second-
 year El Niño and a $> 60\%$ chance of fourth/fifth year La Niña, while La Niña state eruptions show weaker reinforcement of
 both. This mirrors the asymmetric dampening of La Niña relative to El Niño found in Figs. 1, 2, though Fang et al. (2025)
 isolate a fixed eruption type whereas our composites average across eruption season and latitude, plausibly weakening the
 275 signal.

Eruption location introduces a further source of heterogeneity. Following tropical eruptions, Neutral-phase rates shift to
 positive values in both datasets ($1.2yr^{-1}$ models, $1.9yr^{-1}$ reconstructions), the opposite sign to the Neutral-phase dampening
 otherwise seen in the unconditional result, consistent with the tropical-Africa-cooling pathway (Khodri et al., 2017; Pausata
 et al., 2023; D’Agostino et al., 2026) directly promoting El Niño-like growth. NH extratropical eruptions do not reproduce this
 280 signal, instead, they produce the most negative rate in the dataset for La Niña conditions ($-2.0yr^{-1}$, models). This is consistent
 with D’Agostino et al. (2026), who show NH-confined eruptions reinforce an El Niño-like response through three combined
 pathways (southward ITCZ shift, tropical African cooling, and extratropical teleconnection) irrespective of eruption latitude,
 which would manifest as accelerated La Niña decay when expressed as a departure from an ongoing cool phase.

ENSO phase transition probabilities show a consistent, modest increase in phase persistence across both datasets and all
 285 initial phases, with the largest shift for El Niño persistence (19% to 22% in models; 38% to 40% in reconstructions). As
 with the growth and decay rates, this pooled result is better understood as the net average of the opposing season-conditioned
 responses described above. The location-conditioned transition probabilities are more consistent with the phase-conditional



result, with persistence increasing following eruptions at both eruption locations, most notably for La Niña following NH extratropical eruptions (16% to 23% in models).

290 Phase duration distributions provide a further qualitative constraint across all three conditioning schemes. Post-eruption durations in both datasets cluster predominantly at one year across all three initial phases, eruption seasons, and eruption locations, with medians close to the non-volcanic control. This indicates that volcanic forcing does not systematically extend or shorten the duration of the active phase. The exception is the Neutral phase, which shows a wider upper tail (up to ten years in models, nine in reconstructions), persisting under season conditioning (six to seven years) and location conditioning (seven
295 to eight years), consistent with Ohba et al. (2013), Predybaylo et al. (2017), and Predybaylo et al. (2020) on delayed onset of the next active phase following volcanic cooling.

Together, the season and location conditioned results indicate that the unconditional characterisation of volcanic forcing as a uniform dampening of ENSO dynamics is a first appearance. Growth-phase tropical eruptions are associated with a reinforcement of the ongoing anomaly or a positive rather than suppressed Neutral growth signal. In contrast, peak/decay-
300 phase NH extratropical eruptions are associated with collapse toward the Neutral phase or the strongest decay signal. The phase-conditional dampening result therefore appears to be, at least in part, an artefact of pooling across eruptions that differ systematically in eruption timing and source latitude, two of the state-dependent moderators identified by D'Agostino et al. (2026). This does not undermine the phase-conditioned result, which remains directionally consistent across two independent data sources, but should be interpreted as an average outcome rather than evidence of a single, directional independent volcanic
305 effect on ENSO. Except for the SON Neutral suppression, the strongest sub-signals are directionally consistent between models and reconstructions and align with the mechanistic pathways set out by Khodri et al. (2017) and D'Agostino et al. (2026). The consistency of sign and approximate magnitude across two independent datasets, PMIP models and palaeoclimate ENSO reconstructions, is the main basis for treating the pattern as a signal. It should also be noted that eruption magnitude was not considered in this analysis, given the limited number of eruptions once considering, eruption seasonality and location. It
310 remains possible that the underlying dynamics could not scale with larger forcing and that an eruption of far greater magnitude than any in the study period (i.e. a super eruption) could produce a different ENSO response.

5 Conclusions

This study investigated ENSO's response to volcanic forcing during the last millennium through its dynamical evolution by combining climate model simulations of the past with palaeoclimate reconstructions derived from proxies. Comparing PMIP3/4
315 simulations with the Freund et al. (2025) Last Millennium ENSO reconstruction ensemble allowed each diagnostic to be assessed against two independent lines of evidence, providing a stronger basis for distinguishing a volcanic signal from features specific to either dataset. The results of this study provide evidence that volcanic forcing modulates the trajectory of ENSO evolution.

Post-eruption growth and decay rates are predominantly negative in both models and reconstructions, with negative medians
320 occurring when an active El Niño or La Niña phase is underway. However, the significance of the results emerges only against



an observational baseline (Fig. S1), where the neutral phases exhibit strong positive growth and the La Niña phases show sharp decay. Following eruptions, the strong Neutral-phase growth is suppressed toward zero in both datasets, representing the clearest departure from the observational record, while active-phase medians remain negative. At the level of phase-conditioned groupings, none of these differences is distinguishable, reflecting the large internal variability. Transition probabilities show a modest, consistent increase in phase persistence across all starting phases, largest for El Niño, while phase durations remain centred on the control median with no lengthening or shortening. Together these results indicate that volcanic forcing acts to slow the progression of ENSO, suppressing the development of anomalies from Neutral states and accelerating the decay of active phases.

Conditioning these results on eruption season and eruption location shows that this phase-conditioned dampening signal is not a single, uniform response but the net average of two opposing tendencies. Eruptions occurring while an ENSO event is still developing (JJA, SON) reinforce an active phase, whereas eruptions occurring at or after its peak (DJF, MAM) collapse it toward Neutral; the clearest expression of this is the reversal of El Niño persistence following JJA eruptions relative to the sharp La Niña collapse following DJF eruptions. Eruption location produces a comparable divergence: tropical eruptions shift the Neutral-phase growth signal from suppressed to positive, while NH extratropical eruptions produce the most negative decay signal for La Niña. Both asymmetries are directionally consistent between models and reconstructions and align with independent mechanistic pathways (Khodri et al., 2017; Pausata et al., 2020, 2023; D’Agostino et al., 2026), indicating that the unconditional dampening result should be interpreted as an average outcome rather than evidence of a single, direction-independent mechanism.

This study investigated three hypotheses. The first hypothesis (i), that eruptions occurring during an El Niño phase would suppress or weaken that phase, is consistent with the suppression of active El Niño phases. The second hypothesis (ii), that eruptions occurring during a La Niña phase would intensify that event, is contradicted; La Niña phases were dampened rather than intensified. The third hypothesis (iii), that eruptions occurring during a Neutral phase would induce a weak El Niño response, is also contradicted, as the near-zero Neutral response points against a forced shift toward El Niño. This now shows that the response of ENSO depends on eruption timing within the ENSO annual cycle and eruption latitude, not only on pre-eruption ENSO phase, and is most naturally explained by the suppression of the Bjerknes feedback driven through an atmospheric pathway, in line with Khodri et al. (2017) and Pausata et al. (2020, 2023), rather than by a direct oceanic mechanism.

This dynamical framing may help explain some of the long-standing disagreement in the literature: where studies presuppose that volcanic forcing acts on ENSO state or amplitude, phase-preference compositing could plausibly yield inconsistent results across differing eruption selections, background conditions, and analysis windows. The season and location conditioned results offer some support for this idea, suggesting that pooling across eruptions that differ in timing and source latitude, rather than pre-eruption phase alone, may itself be enough to obscure directionally opposite sub-signals. However, the absence of statistical significance means these patterns cannot be distinguished from what would be expected under internal variability alone with the present eruption sample, but the directional agreement across the datasets is suggestive. Future work should prioritise using large model or reconstruction ensembles to increase the sample size available to studies that break down each dataset into ENSO phase and Eruption year groupings. This study built on the ensemble produced by Freund et al. (2025) and future studies should



build upon Last Millennium ENSO reconstructions such as these. Separately, focusing the analysis on periods of sustained, clustered volcanism, such as the thirteenth-to-fifteenth-century activity associated with the onset of the Little Ice Age, could test whether repeated forcing produces decadal-scale shifts in ENSO variance and transition behaviour, and whether the timing-dependent asymmetry identified here still holds under a larger eruption sample with finer-resolved seasonality. Together, these approaches would help establish whether the signals reported in this study reflect a genuine, if weak, volcanic fingerprint on ENSO dynamics.

Code availability. Scripts and Jupyter notebooks for reproducing the analyses and figures are available at the GitHub repository https://github.com/flynnthompson/ENSO_VOLC_LM.

Data availability. Proxy data used in this study are available from Freund et al. (2025). CMIP5/6 and PMIP3/4 models used in this study are listed in Table 2. CMIP and PMIP model simulations are available via the Earth System Grid Federation: <https://esgf.nci.org.au/search>. We acknowledge the World Climate Research Programme, which, through its Working Group on Coupled Modelling, coordinated and promoted CMIP6. We thank the climate modelling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP6 and ESGF. PMIP is endorsed by both WCRP/WGCM and Future Earth/PAGES.

Author contributions. FT contributed to study methodology, performed the analysis, and prepared the manuscript. MBF and JRB contributed to study methodology, results interpretation, and manuscript writing. CT contributed to study methodology, and manuscript writing.

Competing interests. The authors declare that they have no conflict of interest.

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