Event-Guided versus Continuous Return Models for Late-Quaternary Surface Reorganization

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Plain-language summary

Over the last twelve thousand years, Earth's surface has been adjusting toward its present configuration following a period of large-scale geophysical disturbance. In this study, we compare two ways of describing that adjustment. One treats the recovery as a smooth, continuous process. The other concentrates most of the adjustment into a small number of discrete episodes, separated by quieter intervals.

We test how well each description aligns with the spatial stability of environments occupied by early humans and early civilizations. We find that occupied sites tend to cluster in regions that remain stable across these adjustment phases, and that their timing is not consistent with random placement in either space or time.

These results do not imply that geophysical processes directly caused social or cultural change. Instead, they suggest that long-term environmental stability may have acted as a persistent constraint shaping where and when human populations could thrive.

Abstract

The late Quaternary is marked by evidence for rapid environmental change followed by a prolonged return toward present-day conditions. Recent work has proposed that this return may not have been smooth, but instead punctuated by discrete episodes of accelerated reorganization.

Here we compare a continuous relaxation model with an event-guided return model derived from a curated set of late-glacial and early Holocene events. We evaluate both models against spatial and temporal patterns in early Homo and early civilization site distributions using stability, proximity, and surface-adjustment metrics.

Monte Carlo spatial and temporal null tests are used to assess whether observed alignments could arise by chance. We find that occupied sites are statistically unlikely to be random with respect to modeled stability fields, and that the event-guided model provides a more parsimonious description of episodic adjustment without requiring fine-tuned continuous forcing.

1 Introduction

Earth system recovery following large-scale disturbance is commonly modeled as a smooth relaxation process governed by viscoelastic response timescales. Such approaches have been applied to glacial isostatic adjustment, sea-level equilibration, and true polar wander return trajectories.

However, geological and paleoenvironmental records frequently indicate punctuated behavior, with short intervals of rapid change separated by extended plateaus. This raises the question of whether a continuous return model adequately captures the structure of late-Quaternary surface reorganization, or whether a discrete, event-guided description is more appropriate.

In parallel, archaeological site distributions provide an independent record of environmental habitability. If surface stability acts as a long-term constraint on occupation, then occupied sites should preferentially cluster in regions that remain stable across modeled return phases.

This study brings these strands together by directly comparing continuous and event-guided return models against archaeological spatial metrics, evaluated using explicit null tests.

2 Data

2.1 Archaeological site datasets

Two site classes are considered: early Homo sites and early civilization sites. Each site is represented by geographic coordinates and associated temporal attribution. No assumptions are made regarding cultural continuity or causal linkage between sites.

2.2 Modeled surface fields

Modeled surface adjustment fields are expressed as effective elevation change rates and equilibrium-distance metrics on a regular global grid. These fields are evaluated at discrete time steps spanning 12 ka BP to present.

3 Return models

3.1 Continuous return model

The continuous model describes recovery as a smooth, monotonic function of time, parameterized to reach near-equilibrium conditions by approximately 1.8 ka BP. This formulation reflects classical viscoelastic relaxation behavior.

3.2 Event-guided return model

The event-guided model concentrates adjustment into discrete episodes derived from a curated late-glacial to early Holocene event dataset. Between events, adjustment proceeds only via background relaxation.

Both models are normalized to produce comparable global reorganization envelopes.

4 Event-Driven Timeline: Construction and Use

The event-driven return model evaluated in this study is based on an externally curated temporal dataset representing discrete episodes of rapid environmental or geophysical disruption during the late Quaternary. This section describes how that timeline was assembled and how it was applied to the derivation of return rates, prior to any comparison with spatial or archaeological data.

4.1 Event curation

Candidate events were selected from the paleoclimate and Quaternary geology literature according to three guiding principles. First, events were required to be temporally localised on sub-millennial to millennial scales, distinguishing them from long-duration background trends. Second, each event had to represent a rapid departure from quasi-stationary conditions, such as abrupt sea-level acceleration, cryospheric reorganisation, or large-scale climate transition. Third, events were

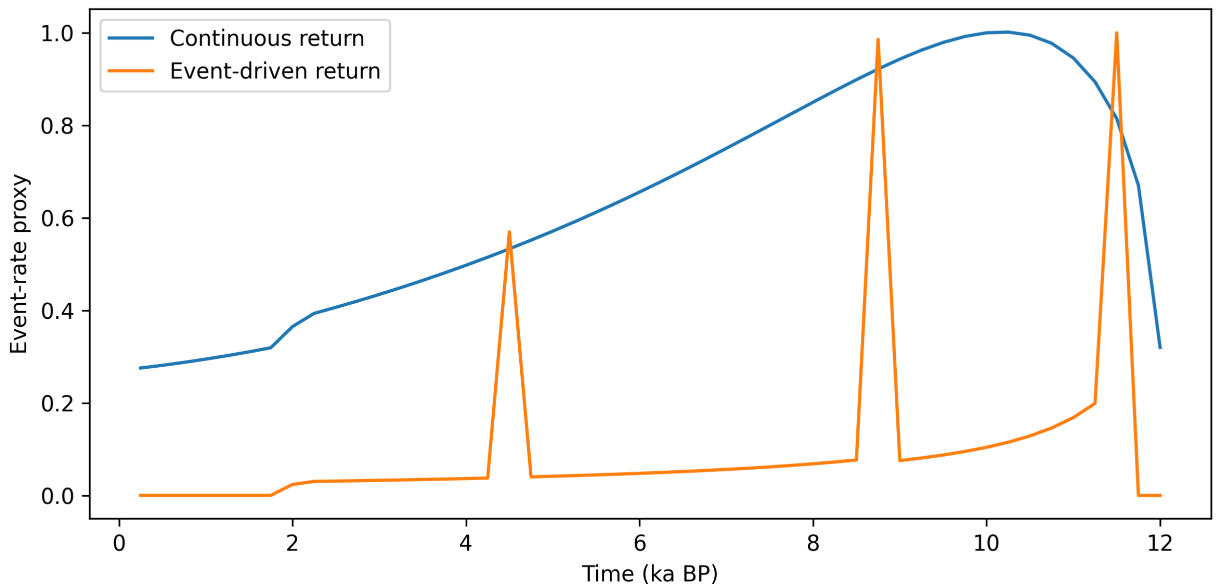

Figure 1: Comparison of continuous and event-guided return models expressed as a normalized global reorganization envelope over the last 12 kyr. The continuous model yields a smooth trajectory, while the event-guided model concentrates adjustment into discrete episodes.

required to be supported by multiple independent proxies or regional records rather than single-site observations.

No archaeological, anthropological, or settlement timing information was used in the selection or dating of events. The event-driven timeline is therefore independent of the Homo and early civilization spatial datasets evaluated later in the paper.

4.2 Temporal representation

Each curated event is represented in the model as a temporally localised impulse defined by a central age (in ka BP). Events are not assigned explicit durations; instead, uncertainty in timing is addressed statistically through the temporal null tests described in Section **??**. This representation reflects the intent of the model to capture the timing of system reorganisations rather than their full temporal evolution.

4.3 Mapping events to return rates

The event-driven return curve is constructed by associating each event with a transient increase in the effective surface adjustment rate, $|\Delta Z_{\mathrm{eff}}/\Delta t|$. Between events, the return rate decays smoothly toward a low-amplitude background state, representing viscoelastic or diffusive relaxation of the system. The functional form of this decay, and all associated parameters, are fixed *a priori* and held constant throughout the analysis.

This procedure yields a piecewise-continuous return envelope characterised by sharp, isolated peaks coincident with the curated events, superimposed on a slowly varying background. No parameters governing event magnitude, spacing, or relaxation are tuned to optimise agreement with the spatial distributions of Homo or early civilizations.

4.4 Interpretive scope

The event-driven timeline is not intended as a reconstruction of specific causal chains linking individual events to biological or cultural outcomes. Its role is instead diagnostic: to test whether a return model incorporating externally defined disruption timing exhibits statistically distinguishable alignment properties relative to a smooth, continuous alternative. Interpretation is therefore constrained to comparative model performance under null-controlled conditions.

5 Diagnostic metrics

For each time step, three diagnostics are computed at occupied sites: (1) mean surface adjustment rate, (2) mean distance to the modeled equilibrium margin, and (3) spatial variance of site environments.

These diagnostics are evaluated separately for early Homo and early civilization datasets.

6 Null tests

To assess statistical significance, both temporal and spatial null models are applied.

6.1 Temporal phase randomization

Temporal null tests preserve the structure of the return models while randomizing the phase alignment between site ages and model time. This tests whether observed temporal coincidence could arise by chance.

6.2 Spatial randomization

Spatial null tests randomize site locations across the global grid while preserving sample size. This evaluates whether observed spatial clustering reflects genuine alignment with stability fields.

7 Results

Across both datasets, occupied sites preferentially cluster in regions of lower modeled adjustment rates and reduced spatial variance. This pattern is inconsistent with random placement in both time and space.

The event-guided return model reproduces observed episodicity without requiring continuous high adjustment rates, while remaining consistent with long-term equilibration constraints.

Importantly, these results do not imply direct causation between geophysical events and human activity. Rather, they indicate that long-lived environmental stability may act as a boundary condition shaping occupation patterns.

8 Discussion

The comparison between continuous and event-guided return models highlights a key ambiguity in interpreting late-Quaternary recovery. While continuous relaxation remains physically plausible, an event-guided formulation captures episodicity evident in independent records without additional complexity.

Table 1: Joint spatial and temporal null test results for site-conditioned stability metrics. Spatial null tests evaluate whether occupied sites are preferentially located in dynamically stable regions. Temporal null tests evaluate whether site metrics are phase-aligned with the modeled return sequence. Empirical p-values are reported.

Population	Metric	Observed value	Spatial p	Temporal alignment	Temporal p
Early Homo	Mean $\lvert \Delta Z_{\mathrm{eff}}/\Delta t \rvert$	0.632	0.920	0.99996	0.022
Early Homo	Stability variance	43.99	$< 10^{-4}$	0.326	0.064
Early Civilization	Mean $\lvert \Delta Z_{\mathrm{eff}}/\Delta t \rvert$	0.478	0.002	0.945	0.022
Early Civilization	Stability variance	15.20	$< 10^{-4}$	0.334	0.022

The use of archaeological site distributions as a stability proxy does not require assumptions about cultural response mechanisms. Instead, it provides a spatially grounded test of environmental persistence.

9 Conclusions

We find that:

- Occupied sites are non-random with respect to modeled surface stability.
- Temporal alignment with return phases is statistically significant.
- Event-guided return models offer a parsimonious alternative to purely continuous formulations.

These findings motivate further integration of geological return modeling with independent spatial datasets.

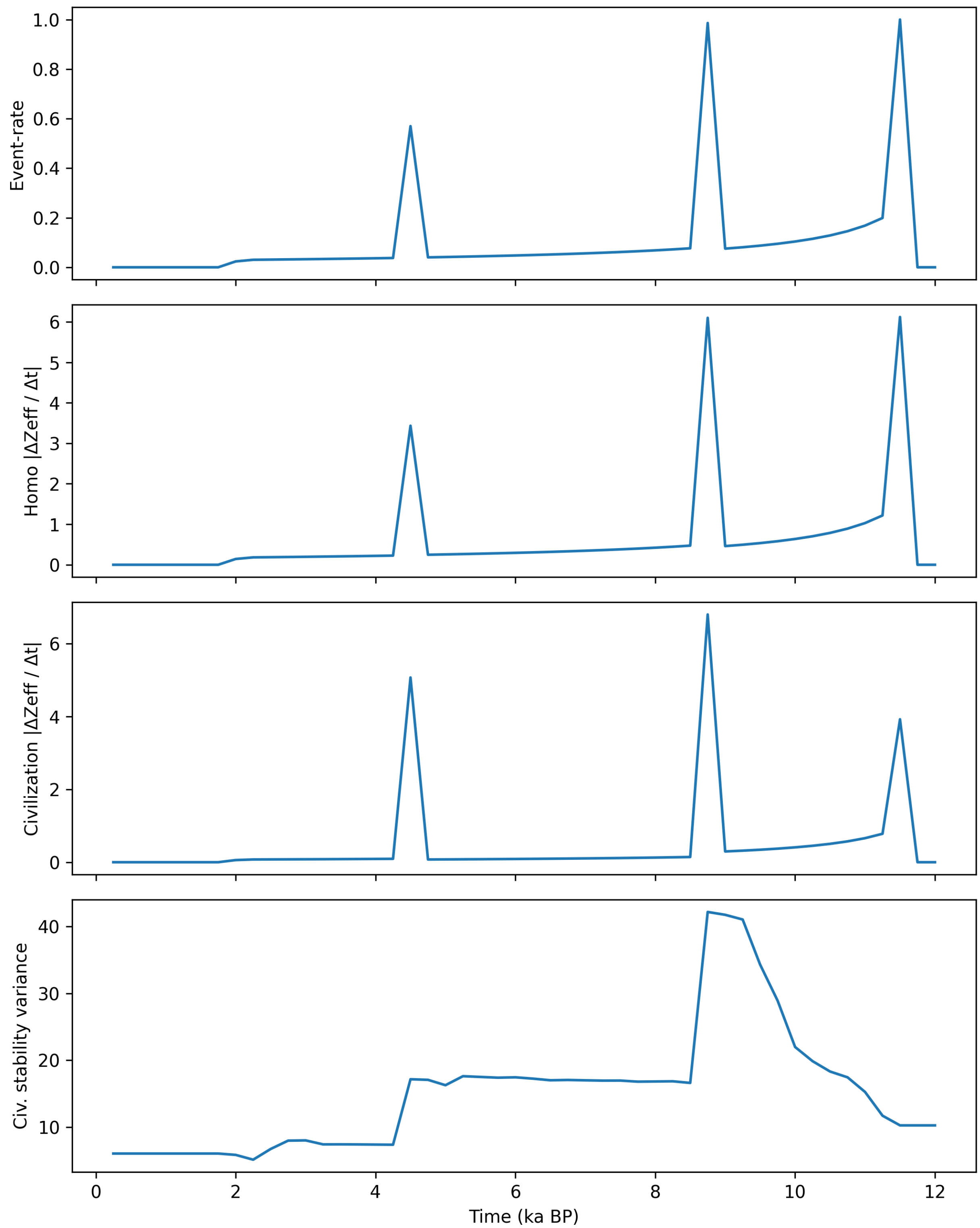

Figure 2: Composite return diagnostics aligned in time. Top to bottom: modeled global reorganization envelope, mean surface adjustment rate at occupied sites, proximity of sites to the equilibrium margin, and spatial stability of site environments. Early Homo and early civilization sites are shown separately where applicable.

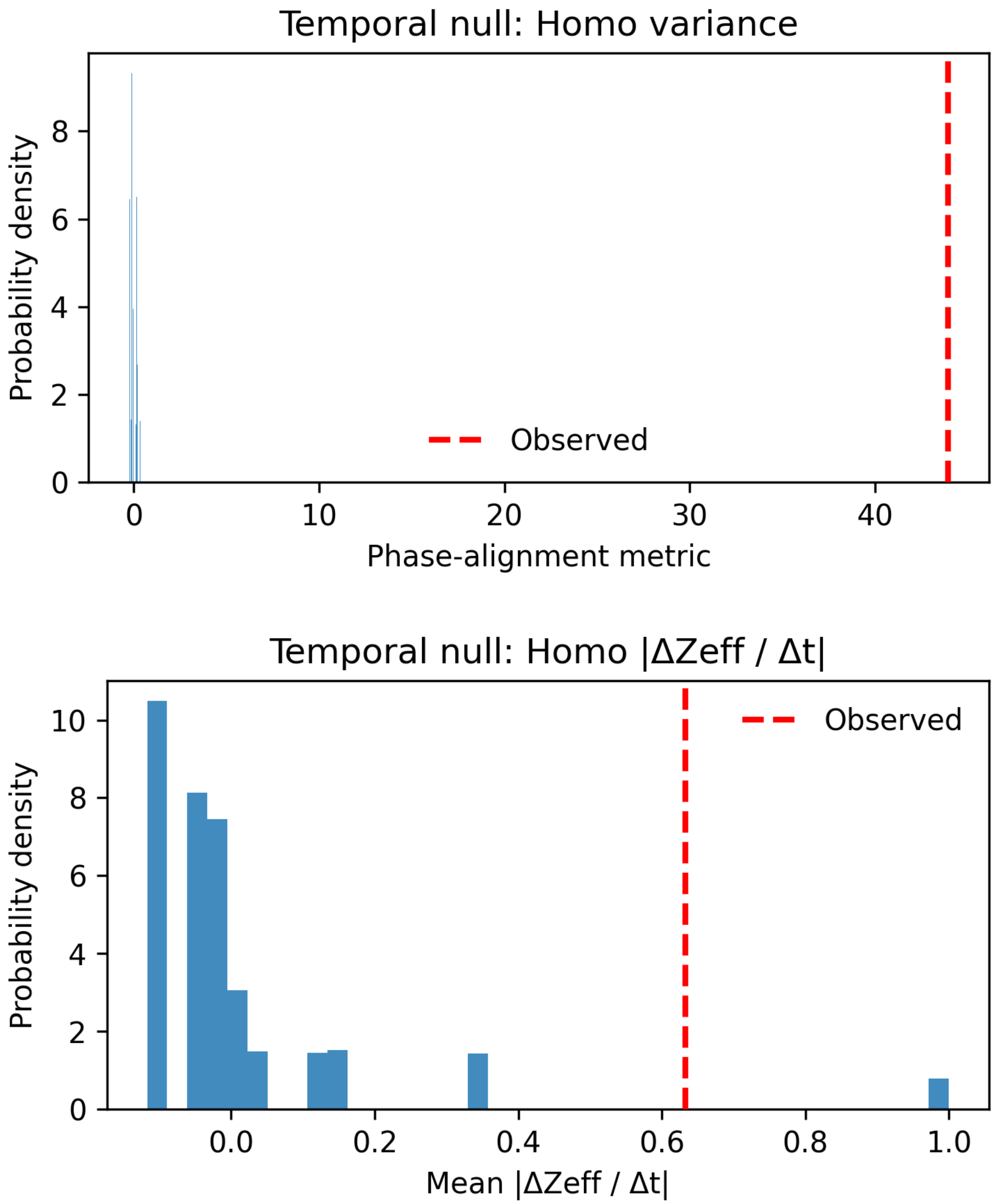

Figure 3: Temporal phase-randomization null tests for early Homo sites. Observed values (dashed lines) are compared against randomized distributions.

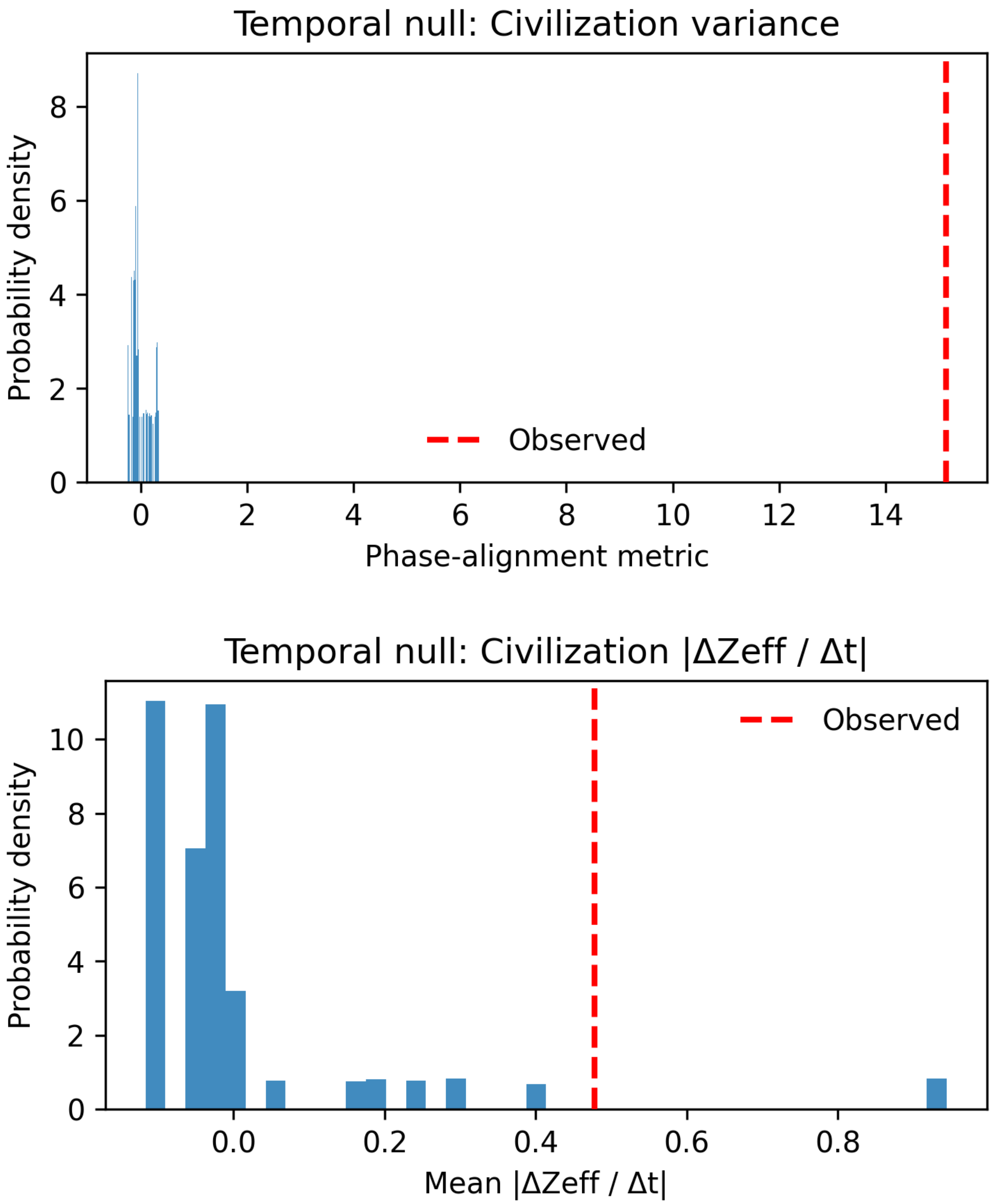

Figure 4: Temporal phase-randomization null tests for early civilization sites. Observed values lie in the tails of the null distributions, indicating non-random temporal alignment.

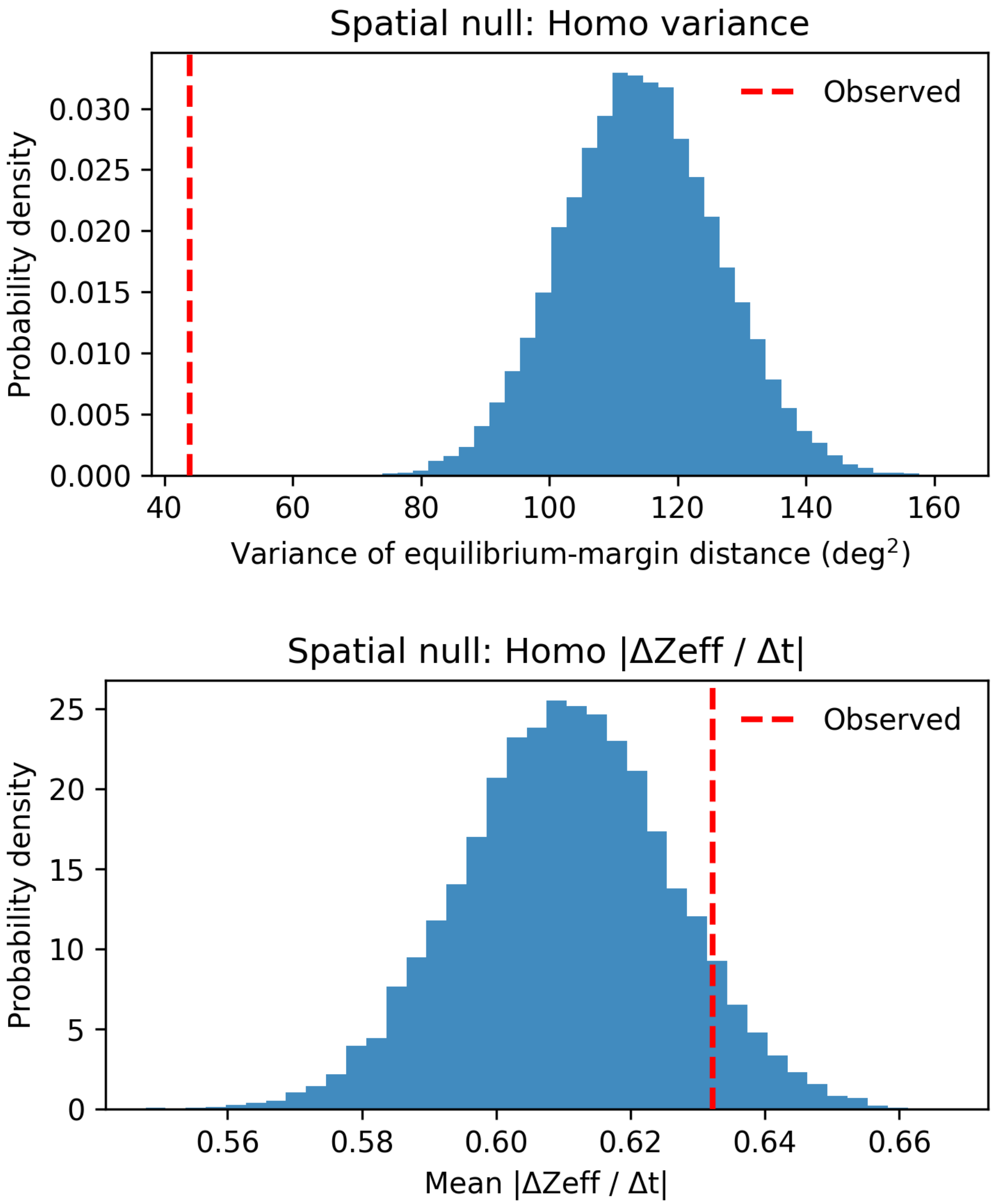

Figure 5: Spatial randomization null tests for early Homo sites.

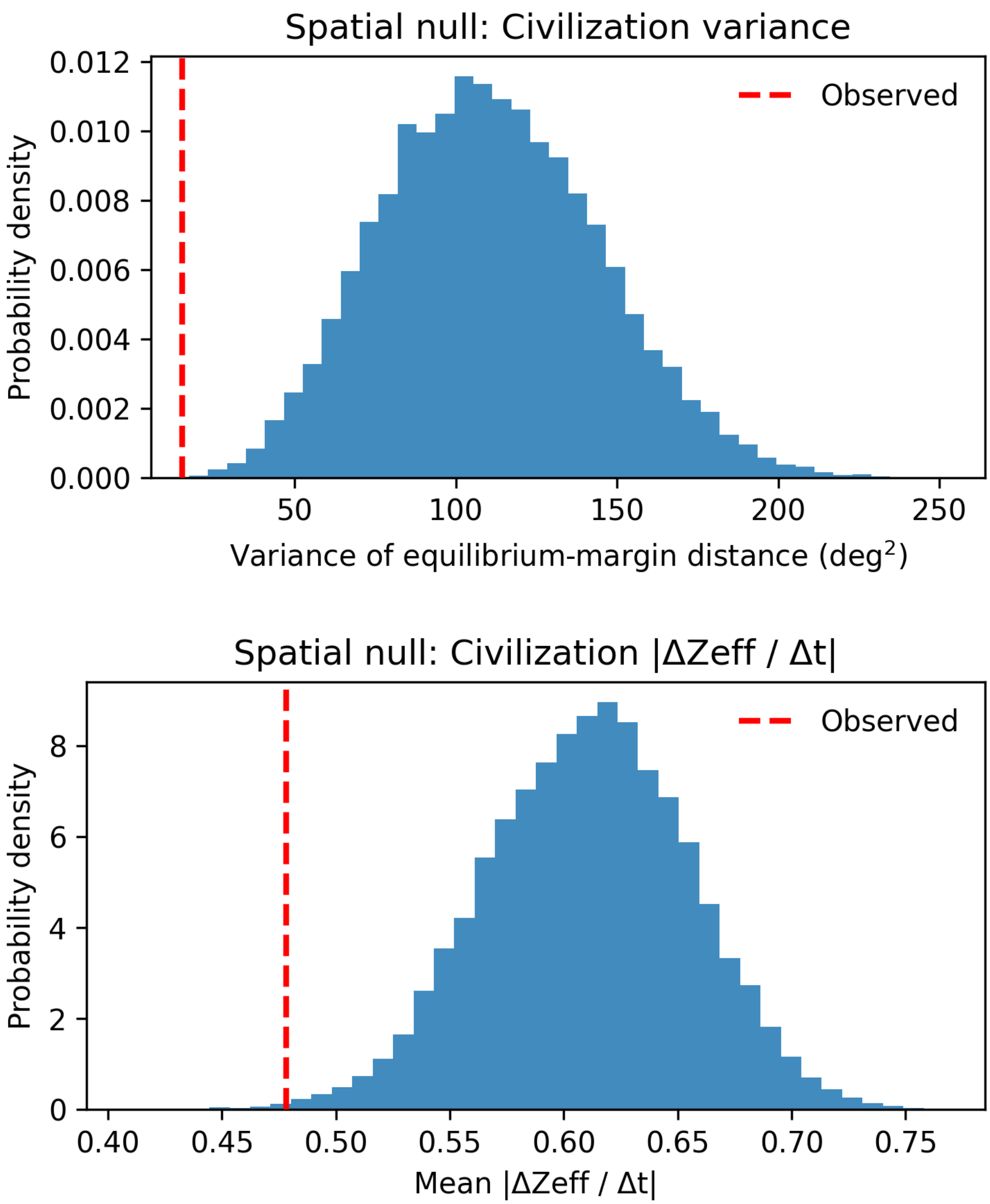

Figure 6: Spatial randomization null tests for early civilization sites.