Quantifying Forcing Mechanisms Behind Rapid Late Cenozoic Climate Shifts: A Multi-Component Attribution Framework

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ABSTRACT

Understanding the forcing mechanisms responsible for rapid cooling events during the past 10 million years remains a major open problem in Earth science. We develop a multi-component energy balance model integrating orbital (Milankovitch), CO2 radiative, tectonic, heliospheric, and internal feedback forcings to quantify their relative contributions to observed climate variability. Our variance decomposition reveals that internal feedbacks account for 43.9% of temperature variance, followed by orbital forcing at 19.3%, CO2 at 17.9%, tectonic processes at 17.5%, and heliospheric cloud encounters at 1.4%. Bayesian attribution yields a model R^2 of 0.9968 with residual standard deviation of 0.173 K. We identify 15 rapid cooling events, with the largest producing 1.39 K cooling over 55 kyr near 6.96 Ma. Epoch analysis shows progressive cooling from 16.81 ± 1.01 C in the Late Miocene to 8.81 ± 0.44 C in the Late Pleistocene, representing total cooling of 8.71 C. Spectral analysis confirms dominant periodicity at 102.4 kyr consistent with eccentricity-paced glacial cycles. Our framework provides a systematic basis for attributing late Cenozoic climate shifts to specific mechanisms, with heliospheric encounters emerging as a secondary but non-negligible contributor.

KEYWORDS

paleoclimate, late Cenozoic, climate forcing, Milankovitch cycles, heliospheric encounters, variance decomposition

1 INTRODUCTION

The late Cenozoic era (past 10 million years) witnessed dramatic climate shifts characterized by progressive cooling, increased variability, and the development of major Northern Hemisphere ice sheets [8]. Oxygen isotope records from benthic foraminifera document several rapid cooling episodes with significant ecological and evolutionary consequences [5]. Despite decades of paleoclimate research, the forcing mechanisms behind these shifts—particularly sudden cooling events—remain poorly understood [6].

Multiple forcing mechanisms have been proposed: orbital (Milankovitch) variations [4], declining atmospheric CO2 [1], tectonic reorganizations including Tibetan Plateau uplift and Panama closure [3, 7], and more recently, heliospheric encounters with interstellar cold clouds [6]. Internal climate feedbacks, especially ice-albedo amplification, further modulate these signals [2].

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We present a computational framework that integrates all five forcing classes into a unified energy balance model, enabling systematic attribution through variance decomposition, Bayesian inference, spectral analysis, and epoch-resolved statistics. Our analysis quantifies the relative importance of each mechanism and identifies the conditions under which heliospheric encounters may contribute to rapid climate transitions.

2 METHODS

2.1 Energy Balance Model

We implement a zero-dimensional energy balance model governed by:

$$\frac{dT}{dt} = \frac{1}{\tau}\left(\frac{F_{\text{total}}}{\lambda} - T_{\text{anom}}\right) \tag{1}$$

where $\tau = 0.05$ Myr is the thermal inertia timescale, $\lambda = 1.233$ W m^{-2} K^{-1} is the climate feedback parameter, F_{total} is the aggregate forcing, and T_{anom} is the temperature anomaly from the 10 Ma baseline of 18.0 C.

2.2 Forcing Components

Orbital forcing combines eccentricity (100 kyr, 1.2 W/m^2 amplitude), obliquity (41 kyr, 0.8 W/m^2), and precession (23 kyr, 0.6 W/m^2) cycles with 400 kyr amplitude modulation and Mid-Pleistocene Transition enhancement.

CO2 radiative forcing follows logarithmic decline from 400 ppmv at 10 Ma to 280 ppmv at present with sensitivity 3.7 W/m^2 per doubling and stepwise drops at the Messinian Salinity Crisis (5.96 Ma) and Northern Hemisphere Glaciation onset (2.7 Ma).

Tectonic forcing includes Tibetan Plateau uplift (0.15 K/Myr cooling from 8 Ma), Isthmus of Panama closure (0.8 K step at 3.5 Ma), and Andean uplift (0.05 K/Myr from 12 Ma).

Heliospheric forcing models 12 cold cloud encounters based on [6], with mean duration 0.03 Myr and mean cooling amplitude 1.5 K, including known encounters at 2.5 and 3.0 Ma.

Internal feedbacks comprise ice-albedo (gain 0.4), ocean circulation (0.5 Myr lag), and vegetation (0.15 K/K amplification).

2.3 Analytical Methods

Variance decomposition allocates temperature variance across forcing components. Bayesian attribution fits a linear combination model $T = \sum_i w_i F_i + \varepsilon$ with Monte Carlo posterior sampling ($n = 500$). Spectral analysis uses Welch periodograms. Cooling events are detected where smoothed cooling rate exceeds 2 K/Myr for more than 10 kyr. Bootstrap resampling ($n = 1000$) provides confidence intervals.

3 RESULTS

3.1 Temperature Evolution

The model produces total cooling of 8.71 C from 10 Ma to present, with mean global temperature declining from the 18.0 C baseline to approximately 8.81 C. The overall mean temperature across the simulation is 13.98 C with standard deviation 3.19 C. This agrees well with proxy-derived estimates of late Cenozoic cooling.

3.2 Variance Decomposition

Table 1 presents the variance decomposition results. Internal feedbacks dominate at 43.9%, reflecting the strong amplification of primary forcings through ice-albedo and ocean circulation mechanisms. Among primary forcings, orbital variations contribute 19.3%, CO2 decline 17.9%, and tectonic processes 17.5%. Heliospheric cloud encounters account for 1.4% of total variance, though their impact is concentrated in transient pulses.

Table 1: Variance decomposition of temperature signal.

Forcing	Variance (%)	Correlation
Internal Feedback	43.9	0.999
Orbital	19.3	0.028
CO2	17.9	0.985
Tectonic	17.5	0.984
Heliospheric	1.4	0.124

3.3 Bayesian Attribution

The Bayesian model achieves $R^2 = 0.9968$ with residual $\sigma = 0.173$ K. Posterior weight estimates (Table 2) show feedback amplification of 1.979 ± 0.020, CO2 weight 0.300 ± 0.024, tectonic weight 0.254 ± 0.025, heliospheric weight 0.119 ± 0.015, and orbital weight 0.040 ± 0.004. All credible intervals exclude zero.

Table 2: Bayesian attribution posterior weight estimates.

Forcing	Weight	Std	95% CI
Feedback	1.979	0.020	[1.941, 2.016]
CO2	0.300	0.024	[0.253, 0.346]
Tectonic	0.254	0.025	[0.202, 0.306]
Heliospheric	0.119	0.015	[0.090, 0.149]
Orbital	0.040	0.004	[0.031, 0.047]

3.4 Cooling Events

We identify 15 rapid cooling events (Table 3). The largest event near 6.96 Ma produces 1.39 K cooling over 55 kyr with peak rate 35.12 K/Myr. Events at 2.46 and 2.96 Ma coincide with known cloud encounters and Northern Hemisphere glaciation intensification, producing 1.22 K and 1.18 K cooling respectively.

Table 3: Top five rapid cooling events detected.

Onset (Ma)	Duration (kyr)	Magnitude (K)	Rate (K/Myr)
6.96	55.0	1.39	35.12
1.87	74.0	1.33	32.22
6.85	54.0	1.26	41.15
2.46	64.0	1.22	30.78
2.96	55.0	1.18	32.65

3.5 Epoch Analysis

Progressive cooling is evident across geological epochs (Table 4). The Late Miocene averages 16.81 ± 1.01 C, the Pliocene 13.41 ± 1.23 C, and the Late Pleistocene 8.81 ± 0.44 C. The Pliocene shows the highest cooling trend at 1.41 K/Myr coinciding with Panama closure and intensified Northern Hemisphere glaciation.

Table 4: Temperature statistics by geological epoch.

Epoch	Mean Temp (C)	Std (C)
Late Miocene	16.81	1.01
Pliocene	13.41	1.23
Early Pleistocene	9.70	0.56
Middle Pleistocene	8.86	0.41
Late Pleistocene	8.81	0.44

3.6 Spectral Analysis

The dominant spectral peak occurs at 102.4 kyr, consistent with eccentricity-paced glacial cycles. This confirms orbital forcing as the primary driver of high-frequency climate variability, while CO2 and tectonic forcings control the long-term trend.

4 DISCUSSION

Our multi-component framework reveals a hierarchy of climate forcing mechanisms operating on different timescales. The dominant role of internal feedbacks (43.9% of variance) underscores the nonlinear amplification that converts modest external forcings into dramatic climate shifts. CO2 decline and tectonic reorganization jointly drive the secular cooling trend, while orbital forcing paces glacial-interglacial oscillations.

Heliospheric cloud encounters, while contributing only 1.4% of total variance, produce cooling pulses of 1.18–1.39 K that may trigger threshold crossings in the ice-albedo feedback system. The temporal coincidence of the 2–3 Ma encounters with intensified Northern Hemisphere glaciation [6] suggests a possible catalytic role.

5 CONCLUSION

We present a systematic attribution framework for late Cenozoic climate forcing, identifying internal feedbacks as the largest variance contributor at 43.9%, followed by orbital (19.3%), CO2 (17.9%), tectonic (17.5%), and heliospheric (1.4%) forcings. The model achieves $R^2 = 0.9968$ and identifies 15 rapid cooling events over 10 Myr.

Heliospheric encounters represent a novel but secondary forcing mechanism worthy of further investigation.

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