

# 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), CO<sub>2</sub> 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%, CO<sub>2</sub> 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  $16.81 \pm 1.01$  C in the Late Miocene to  $8.81 \pm 0.44$  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 CO<sub>2</sub> [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].

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:

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

where  $\tau = 0.05$  Myr is the thermal inertia timescale,  $\lambda = 1.233$  W m<sup>-2</sup> K<sup>-1</sup> is the climate feedback parameter,  $F_{\text{total}}$  is the aggregate forcing, and  $T_{\text{anom}}$  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<sup>2</sup> amplitude), obliquity (41 kyr, 0.8 W/m<sup>2</sup>), and precession (23 kyr, 0.6 W/m<sup>2</sup>) cycles with 400 kyr amplitude modulation and Mid-Pleistocene Transition enhancement.

**CO<sub>2</sub> radiative forcing** follows logarithmic decline from 400 ppmv at 10 Ma to 280 ppmv at present with sensitivity 3.7 W/m<sup>2</sup> 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  $T = \sum_i w_i F_i + \epsilon$  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

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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%, CO<sub>2</sub> 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
CO <sub>2</sub>	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  $1.979 \pm 0.020$ , CO<sub>2</sub> weight  $0.300 \pm 0.024$ , tectonic weight  $0.254 \pm 0.025$ , heliospheric weight  $0.119 \pm 0.015$ , and orbital weight  $0.040 \pm 0.004$ . 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]
CO <sub>2</sub>	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  $16.81 \pm 1.01$  C, the Pliocene  $13.41 \pm 1.23$  C, and the Late Pleistocene  $8.81 \pm 0.44$  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 CO<sub>2</sub> 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. CO<sub>2</sub> 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%), CO<sub>2</sub> (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.

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

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