

# CLIMATE SENSITIVITY IN A PRE-PLANT WORLD

## Why High CO<sub>2</sub> May Not Have Been Sufficient to Maintain a Paleozoic Hothouse

Earth's climate history is usually told as a story of greenhouse gases, although in fact it has not been controlled by greenhouse gases alone. Over geological time, the position of continents, the presence or absence of vegetation, and the extent of sea ice have all shaped how the planet absorbs, stores, and redistributes heat. These boundary conditions help determine not only the climate state itself, but also how strongly Earth responds to a changes atmospheric CO<sub>2</sub>.

In this study, we explore how that background state might have changed through the Phanerozoic by comparing vegetated, no-vegetation, and realistic-vegetation intermediate complexity climate simulations across time. Our results suggest that Earth's climates, especially in the Paleozoic, can sit far from a simple CO<sub>2</sub>-based expectation, suggesting that geography, surface properties, and feedbacks such as sea ice played a major role in setting the climate baseline.

The implication is that Earth's climate sensitivity is not fixed in time. It depends on the evolving interaction between greenhouse forcing, polar geography, and feedbacks such as sea ice and albedo. In other words, the earlier Earth was not just a simpler version of today's climate system, but a different one altogether.

When global mean surface temperature (GMST) is expressed as a residual relative to the GMST log-CO<sub>2</sub> relationship, the simulations with no vegetation in the Paleozoic show a pronounced negative anomaly (Fig. 1). The largest departures occur in the oldest intervals, where the climate is substantially colder than the vegetated baseline would predict, while later intervals cluster much closer to the reference trend.

The CO<sub>2</sub>-doubling response varies through the Phanerozoic rather than remaining constant (Fig. 2). In the absence of global land vegetation, the climate sensitivity is highly geography dependent and generally lower in the Paleozoic than during the rest of the eon. Introducing vegetation into the Earth system keeps it's climate sensitivity rather stable and buffers the effect of geographic changes from plate tectonics.

Sea-ice response also changes through time and tracks the same broad era dependence. In the no-vegetation simulations, the sea-ice response is generally weaker in the Paleozoic than in later eras, which might be related to the southern hemispheric continental geometry, likely influencing climate sensitivity as well.

For fun and because we haven't run the proper high-CO<sub>2</sub> simulations yet, we scaled GMST to the COPSE CO<sub>2</sub> curve (Lenton et al., 2018) using the logarithmic relationship (Fig. 4). The realistic-vegetation simulations remain colder than the vegetated reference in the early Paleozoic. The offset is largest before roughly 383 Ma, where the realistic vegetation state sits well below the vegetated expectation and implies a substantial additional CO<sub>2</sub> requirement to compensate for the temperature difference. This result supports the idea that the early Paleozoic climate baseline was set by boundary conditions as well as greenhouse forcing and leaves us guessing if either pCO<sub>2</sub> was really freaking high, more vegetation than we think was around already or the Paleozoic was colder than we think (see also Fig. 5).

Niklas Werner<sup>\*1</sup>, Florian Franziskakis<sup>2</sup>, Andrew Merdith<sup>3</sup>, Christian Vèrard<sup>4</sup>, Maura Brunetti<sup>3</sup>, Taras Gerya<sup>1</sup> and Paul Tackley<sup>1</sup>

<sup>1</sup>Department of Earth and Planetary Science, ETH Zurich, Switzerland

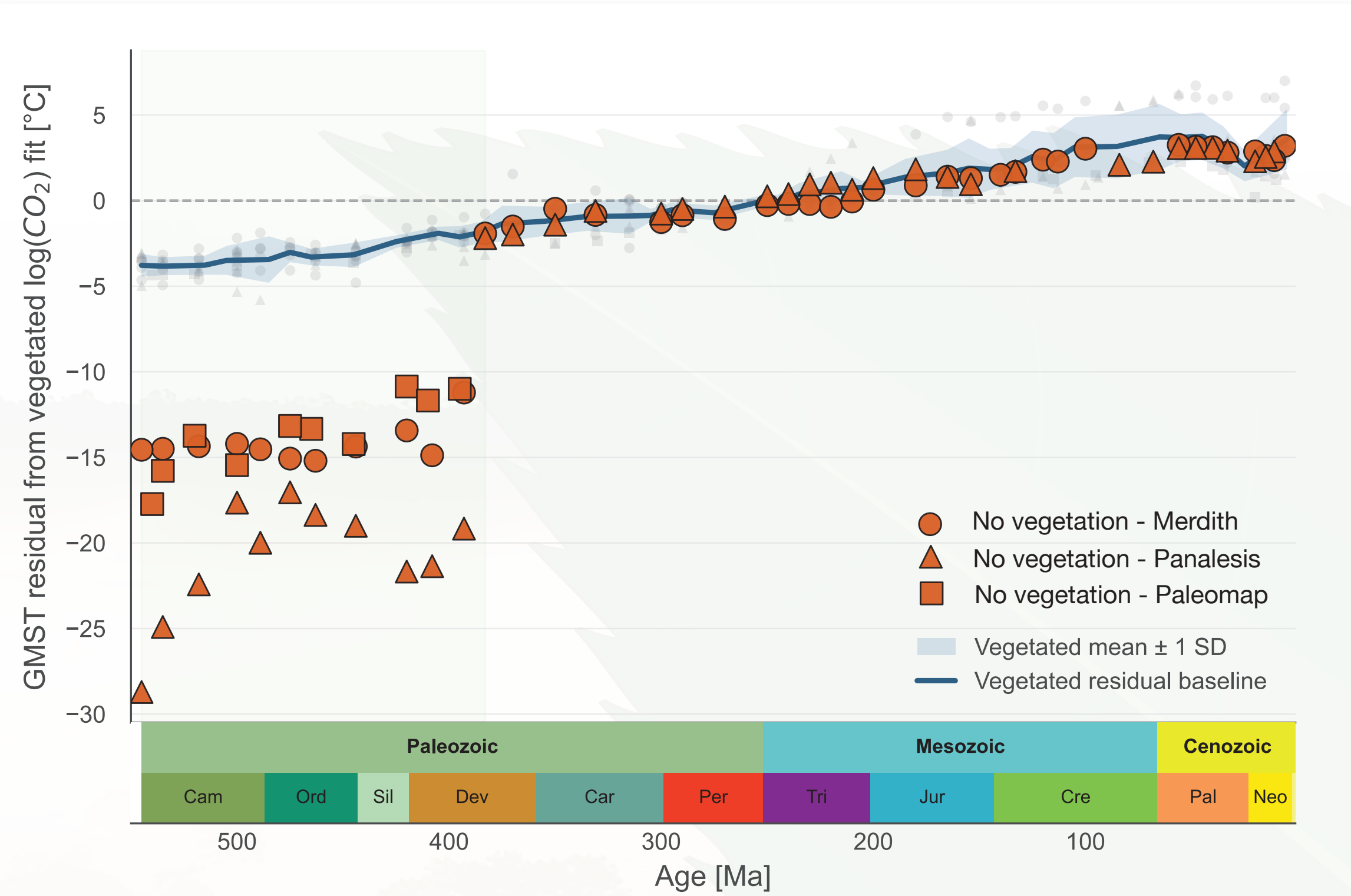
<sup>2</sup>Institute for Environmental Sciences, University of Geneva, Geneva, Switzerland, Geneva, Switzerland

<sup>3</sup>School of Physics, Chemistry and Earth Science, University of Adelaide, Adelaide, SA, Australia

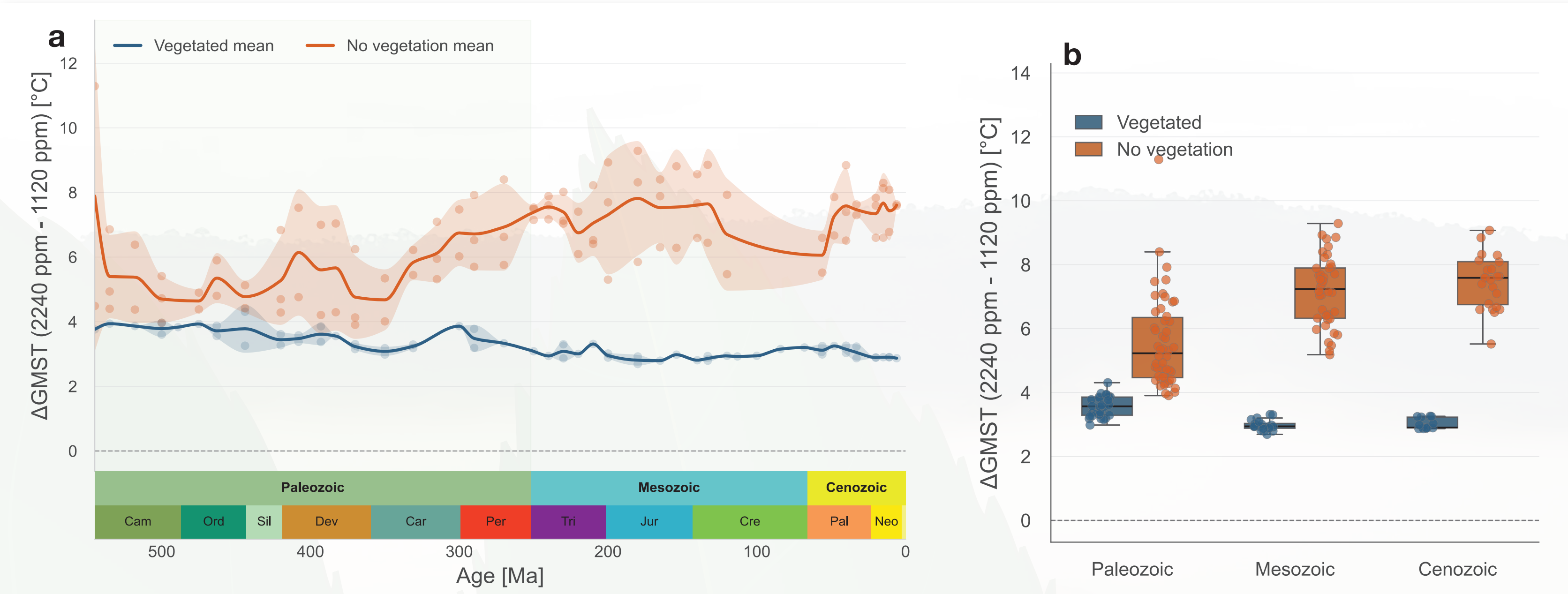
<sup>4</sup>Department of Earth Sciences, University of Geneva

### METHODS

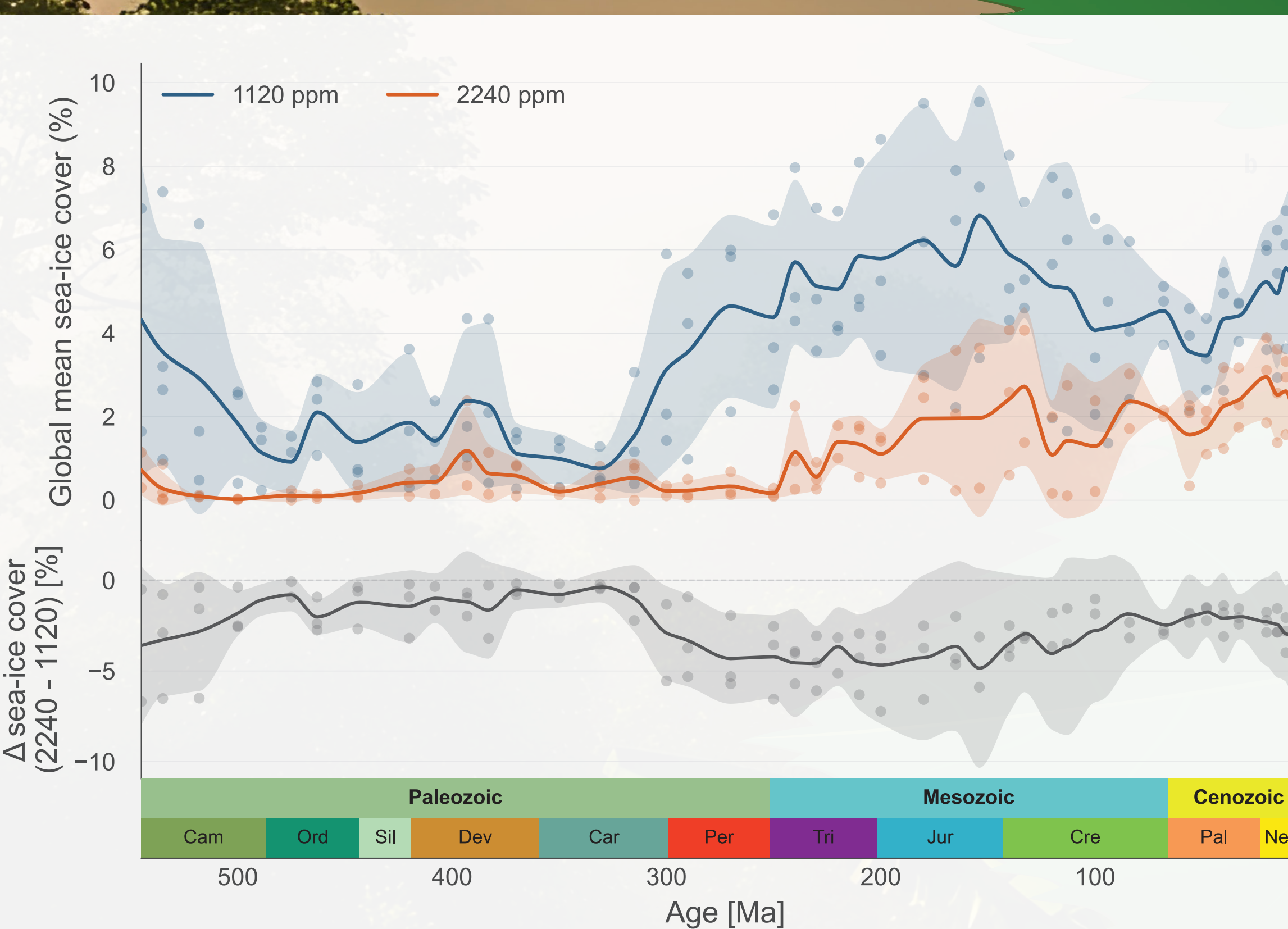
We used the PLASIM-Genie climate model to simulate Phanerozoic climate states across three paleogeographic reconstructions, Merdith, Paleomap, and Panaleis, at two fixed CO<sub>2</sub> levels, 1120 and 2240 ppm. For the no-vegetation case, we used the baseline simulations with vegetation removed from the land surface. The vegetated simulations include a decreasing solar constant backward in time, and the realistic-vegetation runs prescribe vegetation-like albedo and roughness length conditions up to 383 Ma to mimic early land vegetation before transitioning to the standard vegetated setup. From these simulations, we extracted global mean surface temperature, sea-ice cover, and related radiative diagnostics, then compared responses across geological age and era using residuals, boxplots, and time series.



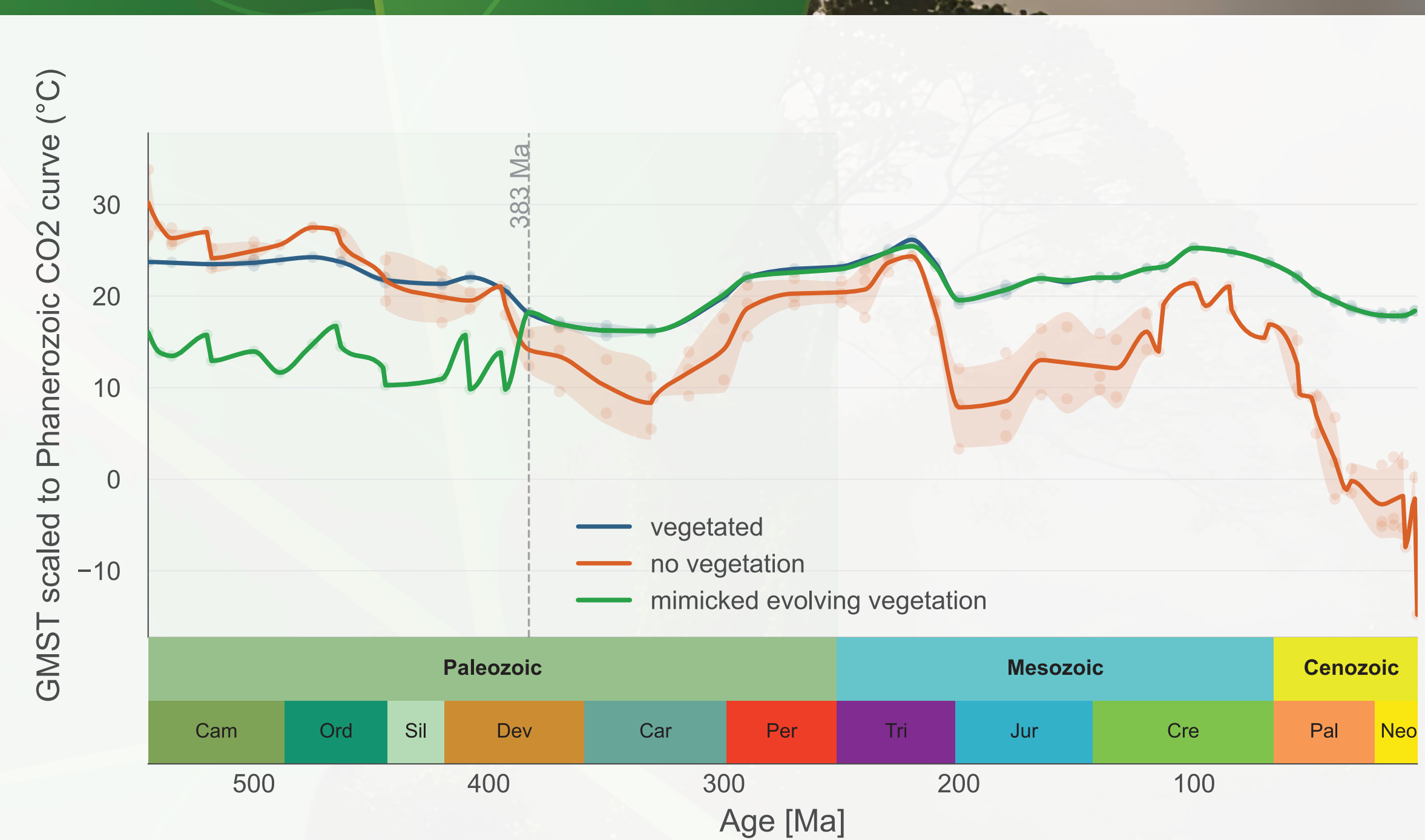
**Fig. 1. Early Paleozoic climate departures from the CO<sub>2</sub>-GMST relationship.** This figure shows GMST expressed as residuals from the vegetated log-CO<sub>2</sub> baseline, allowing the no-vegetation benchmark to be compared directly against the climate state expected from CO<sub>2</sub> alone. Grey points show individual vegetated simulations, the blue band and line summarize the smoothed vegetated relationship, and the orange points mark the no-vegetation 1120 ppm benchmark. The strongest negative residuals occur in the early Paleozoic, where the climate is substantially colder than the vegetated CO<sub>2</sub> trend would predict, while later intervals lie much closer to the reference baseline. This pattern suggests that early Phanerozoic climate states were strongly influenced by boundary conditions beyond greenhouse forcing, rather than by CO<sub>2</sub> alone.



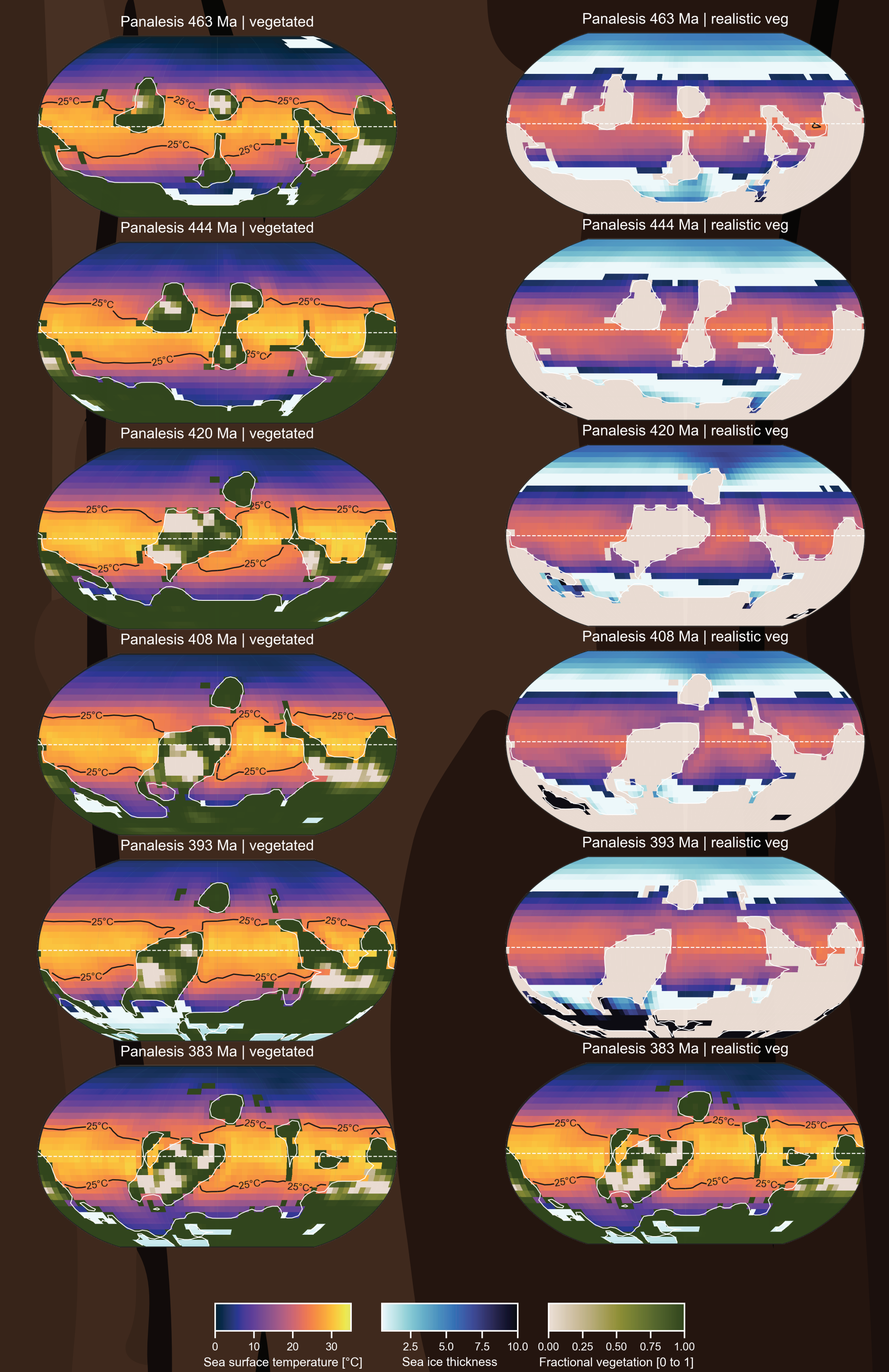
**Fig. 2. Climate sensitivity through the Phanerozoic.** Panel A shows the CO<sub>2</sub>-doubling response through time, with climate sensitivity defined as the GMST difference between 2240 ppm and 1120 ppm. Smoothed mean trajectories are shown for vegetated and no-vegetation simulations, with individual reconstruction values plotted faintly in the background and the geological time scale shown below. Panel B summarizes the same response by geological era as boxplots, highlighting the spread of values within each era and the contrast between vegetated and no-vegetation boundary states. Together, the panels show that climate sensitivity is not constant through time, but varies with both boundary conditions and geological age.



**Fig. 3. No-vegetation sea-ice response through the Phanerozoic.** This figure shows global mean sea-ice cover for the no-vegetation simulations at 1120 ppm and 2240 ppm, together with the CO<sub>2</sub>-doubling response defined as the difference between the two states. Smoothed means are shown with uncertainty bands, and individual reconstruction values are plotted as faint points in the background. The geological time scale is shown below the main panels. The figure highlights that sea-ice sensitivity varies through time and is strongest in the older part of the record, consistent with a colder background climate and stronger high-latitude feedbacks in the early Phanerozoic.



**Fig. 4. GMST scaled to a Phanerozoic CO<sub>2</sub> curve.** This figure compares the vegetated, no-vegetation, and realistic-vegetation GMST reconstructions after scaling them to a common Phanerozoic CO<sub>2</sub> trajectory (Lenton et al., 2018). Somewhat arbitrarily we kick in dynamic vegetation in the model at 383 Ma. Since there was already some vegetation around by that time we mimic the physical impact this would have on albedo and boundary layer circulation by prescribing the albedo and surface roughness. Despite scaling the GMST to up to 6000 ppm in the early Paleozoic, the absence of vegetation and a lower solar constant are enough to keep the climate significantly colder. It is important to note here, that the vegetated and mimicked evolving vegetation simulations here have a decreasing solar constant over time, while it is fixed to its present-day value in the no-vegetation simulations.



**Fig. 5. Comparison of Panaleis palaeoclimate simulations with realistic vegetation prescribed from reconstructed biomes and fully vegetated land cover.** Panels show sea surface temperature, sea ice thickness, and land vegetation fraction for selected time slices, with coastlines derived from the reconstructed land-sea mask and the equator marked for reference. The figure highlights that vegetation helps maintain a warmer climate at the same CO<sub>2</sub> level, whereas comparable warmth would likely require substantially higher CO<sub>2</sub> without vegetation.