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PlioVAR to PlioMioVAR – a treasure trove to constrain future warmer climate

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The PAGES working group PlioMioVAR curates records of past climate change from ocean and terrestrial archives over the last ~2–23 Myr to reconstruct climate evolution and facilitate data-climate model comparisons.

Overview

Ocean and terrestrial sediment archives of past climate change are integral to our understanding of future climate change. The Pliocene and Miocene epochs are useful pseudo-analogs for future climate change. They are the most recent periods of sustained warmth where carbon dioxide concentration estimates are similar to, or higher than, modern anthropogenic levels, and the continental configuration was similar to today. A primary focus of the PAGES PlioMioVAR working group is to curate high-quality databases to facilitate comparisons with climate models and explore climate transitions over the last ~2 to 23 Myr. In this article we discuss the results and considerations of data-model comparisons, multi-proxy reconstructions, and constraining age models for ocean-sediment-based records and vegetation reconstructions.

Paleoreconstructions and climate-model comparisons

Paleoreconstructions from the International Ocean Discovery Program (IODP) and its predecessors (e.g. Ocean Drilling Program, ODP) have been, and continue to be, central to the success of the Paleoclimate Modelling Intercomparison Project (PMIP). For the Pliocene, PlioVAR and Pliocene Research, Interpretation and Synoptic Mapping (PRISM) efforts (Dowsett et al. 2023; McClymont et al. 2020) are essential for the Pliocene Model Intercomparison Project (PlioMIP); comparing the outputs of climate models to proxy data allow us to assess performance and highlight uncertainties. This is particularly important considering the potential of the Pliocene to be used as an analog for warming in the near-term future, as referenced in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2021).

The recent PlioVAR-PlioMIP2 comparison estimates global mean sea-surface temperatures during Pliocene interglacial KM5c (3.205 +/ 0.02 Myr ago) to be ~2.3°C warmer than the pre-industrial (PI 1870–1899; McClymont et al. 2020), comparable to projections for 2100 CE. Burton et al. (2024) show that this change is predominantly driven by CO_2 forcing at the majority of proxy data sites (Fig. 1), though there is some data-model mismatch. For example, an outstanding issue from data-model comparison efforts is that paleoreconstructions are consistently warmer in mid- to high-latitude regions in comparison to model outputs. The magnitude of this difference can vary between proxy types, suggesting possible seasonal bias in our proxy reconstructions and/or model limitations in simulating polar amplification. PlioMIP3 (Haywood et al. 2024) will include early Pliocene targets and there is also expanding interest in developing modeling targets for the Miocene (Steinthorsdottir et al. 2021).

Paleoreconstructions from multiple proxies

Understanding past warm climates requires the estimation of key oceanographic variables, such as ocean temperatures (McClymont et al. 2020). Sea-surface temperature (SST), at the interface of the atmosphere and ocean, reflects air–sea heat exchange, meridional heat transport and large-scale ocean circulation. As a result, continuous SST records spanning millions of years have been generated using drilled marine-sediment cores. Various approaches, such as microfossil assemblages, geochemical signals from the calcite shells and the distribution of lipid biomarkers can be used to indirectly infer SST from marine sediments (Judd et al. 2022).

Over the last two decades, the Mg/Ca ratio of planktonic foraminifera shell, the $U^{K'}_{37}$ index based on haptophyte algae, and the TEX_{86} index based on marine archaea, have been widely employed for SST reconstructions (Judd et al. 2020; McClymont et al. 2020). These so-called temperature proxies, also referred to as paleothermometers, each have their own advantages and limitations. For example, organic proxies like $U^{K'}_{37}$ and TEX_{86} can be used in sediment cores retrieved

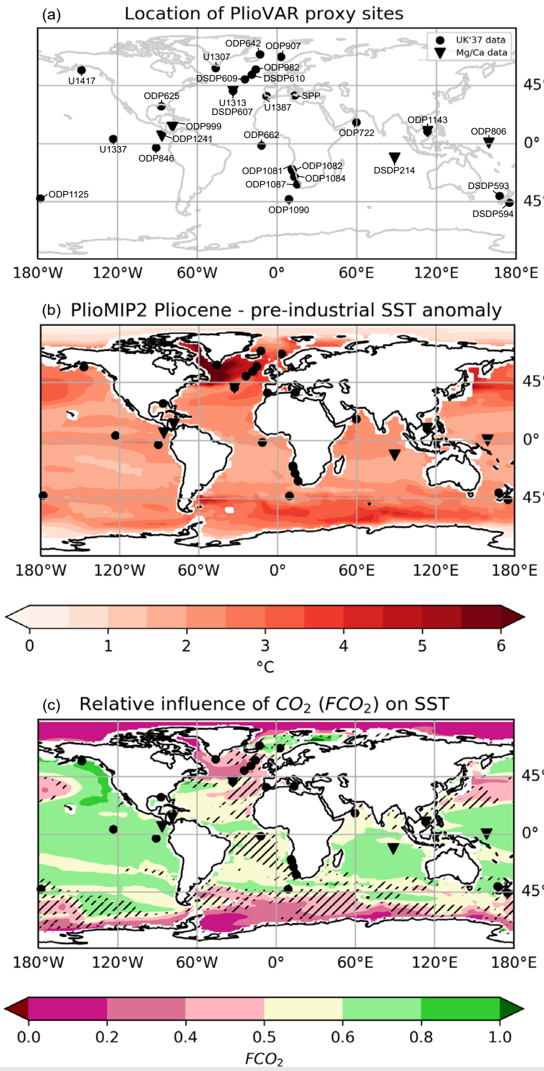

Figure 1: (A) Location of PlioVAR proxy data sites; $U^{K'}_{37}$ sites are denoted by a circle, and Mg/Ca sites are denoted by a triangle. **(B)** PlioMIP2 multi-model mean Pliocene-PI sea-surface temperature anomaly. **(C)** FCO_2 (influence of CO_2 forcing) on (B). CO_2 forcing strongly impacts the temperature in the green regions. Hatching represents uncertainty between models. Figure adapted from Burton et al. (2024) under the CC-BY-4.0 license.

from deep-ocean basins, located below the carbonate compensation depth where sediments are devoid of calcite shells. However, the $U^{K'}_{37}$ proxy saturates at ~28°C, while TEX_{86} may reflect shallow subsurface temperature rather than the SST in certain settings. The foraminiferal Mg/Ca proxy is particularly suitable for studying tropical oceans during past warm climates, where foraminifera shells are abundant in sediments. Nonetheless, the Mg/Ca ratio of planktonic foraminifera also varies due to non-thermal factors, such as changes in seawater chemistry (Mg/Ca ratio, salinity and pH). Therefore, a multi-proxy approach offers an opportunity to leverage the strengths of each proxy in estimating SST and to expand the spatial coverage of SST estimates on a global scale. This is particularly important for the reconstruction of meridional temperature gradients, i.e. the difference in SST between low latitudes and mid-high latitudes, which is crucial for calculating Earth System Sensitivity for the IPCC.

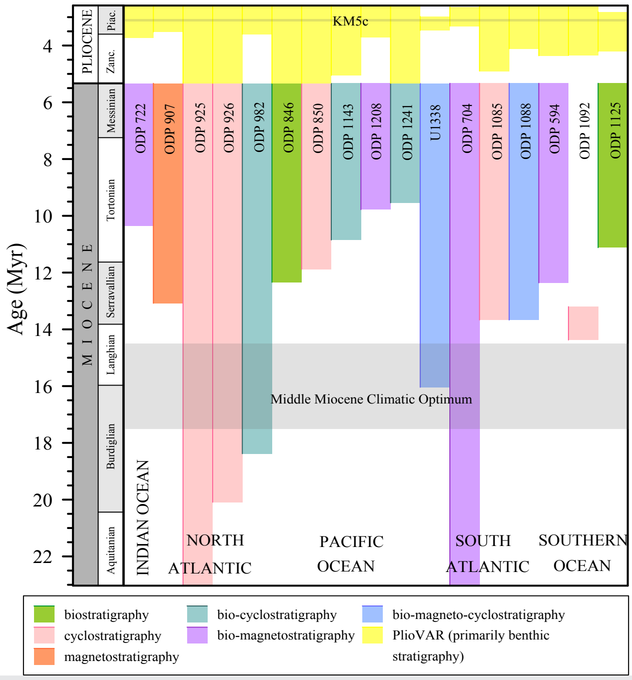

Figure 2: Stratigraphic age ranges and methods used at various ODP and IODP sites across different ocean basins within PlioMioVAR.

Age models

Accurate age models of marine-sediment records provide a crucial temporal framework necessary to interpret paleoclimate data and compare them with climate-model simulations. Developing reliable age models requires understanding the stratigraphic nature of existing age models, and collaboration between scientists working in various paleoproxies and age modeling techniques (biostratigraphy, magnetostratigraphy, astrochronology).

The PlioVAR initiative focused on targeted intervals for model-data comparison (KM5c, McClymont et al. 2020; late Pliocene to early Pleistocene, 3.3–2.4 Myr ago, McClymont et al. 2023), emphasizing orbital-scale variability and age-model refinements on thousand-year timescales. The biggest hurdle in this process is achieving precise synchronization between different datasets, which involves resolving discrepancies in sedimentation rates and calibrating proxy data to absolute timescales. Building on this, the MioOcean efforts within the PlioMioVAR working group expand into the Miocene, examining long-term trends from 23 to 5 Myr ago, and key intervals such as the Miocene Climatic Optimum (Fig. 2). This expansion requires consideration of existing stratigraphic markers across the ocean-drilling repository and assessing orbital-scale variability, where achievable, in available sediment cores or paleoclimate reconstructions.

Establishing a robust Miocene chronology for the MioOcean faces several challenges. The extensive interval spans nearly 18 Myr, complicating the establishment of continuous age models. Certain intervals, particularly within the Lower and Middle Miocene, remain challenging due to incomplete data recovery caused by drilling difficulties and sedimentological hiatuses, and/or muted glacial–interglacial variability. This highlights the need for better aligning different chronological approaches for these complex intervals. These hurdles underscore the importance of age-model validation and enhanced collaboration among scientists where transfer of site-specific knowledge is used to refine age models accurately. Of utmost importance to the success of PlioVAR, and now PlioMioVAR, is proper compilation and archival of climate records. Comprehensive data reporting with detailed sampling information is essential for data reuse, reproducibility and updates with new climate proxy records. Age-model estimations may be revised as methodologies evolve, making reproducible and reusable data crucial for ongoing refinement and development. This ensures the longevity of these datasets, allowing continual use by current and future scientists.

Vegetation reconstructions

Vegetation reconstructions from oceanic and terrestrial archives are a key component in climate reconstructions. Hydroclimate and biome reconstructions reveal information about the habitability of coastal and inland communities. Application of biomarkers in marine sediment (e.g. Bhattacharya et al. 2022) can reconstruct monsoon seasonal timing and intensity. Terrestrial archives are also needed to complement marine records, to provide spatial coverage of the other third of the Earth's surface and offer insights into additional climate processes (Baker 2009).

Terrestrial source material for precipitation reconstruction can be found in terrestrial, lacustrine and marine-sedimentary archives to which terrestrial sediments and organic remains may be transported or found in situ. Remains of vegetation can be used to reconstruct precipitation through community-based morphology and molecular methods, while paleosols, isotopic analysis of speleothems, paleolake extent reconstructed from multiple lines of data, and many others, can all be used to understand different components of past hydroclimate.

To complement marine-focused paleoreconstruction databases such as PlioMioVAR, the Neogene Terrestrial Climate database aims to curate terrestrial climate reconstructions to enhance data-model comparisons. This database includes seasonal climate for both temperature and hydroclimate variables and from any available terrestrial proxy archive. Based in WDS-Paleo, the database will be updatable over time to include new datasets, new proxies and emerging needs of the paleoclimate modeling community.

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