



MioOcean: database compilation and temperature proxy systematics in the Miocene oceans

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Abstract: The Miocene epoch has been highlighted as containing reference intervals for near future warmer climates; however, to realize the full potential of this analogue, discrepancies must be addressed, including those between model predictions and proxy data for ocean temperatures. Over recent years, new insights into ocean temperature proxy systematics have come to light, thus providing robust Miocene ocean temperature estimates requires re-evaluation of available data. In tandem, collaboration between stratigraphers and geochemists emphasises the importance of refining and synchronising age models to ensure robust comparisons of temperature patterns across space and time. Here, we compiled published Miocene temperature proxy records from 101 publications and 94 sites into the new MioOcean database, recalculated temperatures using state of the art proxy constraints, and revised and/or verified age models for 38 key sites. The MioOcean database includes upper and bottom ocean temperature records from organic ($U^{K'_{37}}$ and TEX_{86}) and inorganic (Mg/Ca, $\delta^{18}O$, and Δ_{47}) marine geochemical proxies. To improve confidence in, and comparability between, datasets, we convert proxies into temperature in an internally consistent manner, including updating all associated input variables. To aid usability, the database provides propagated numerical uncertainty estimates encompassing as many sources of error as possible. The MioOcean database improves accessibility of proxy-based Miocene ocean temperature reconstructions to non-specialists, simplifies model-data comparison and validation, and provides the necessary groundwork for in-depth inter-proxy comparison studies. The data compilation (<https://doi.org/10.5281/zenodo.22258386>, Sosdian et al., 2026) is also hosted on www.mioocean.com, including interactive data visualization, enabling interrogation and comparison of re-evaluated MioOcean records.

1 Introduction

Understanding Earth's past climate has long been recognized as critical to reliably predicting future change associated with anthropogenic warming. Overall, the Miocene was generally warmer and wetter, and multiple episodes of climate change are documented (Steinthorsdottir et al., 2021 and references therein). Intervals of the Miocene (23.03–5.33 Ma) have been highlighted as potentially useful analogues for future climate, as both atmospheric CO_2 concentrations and global mean surface temperature changes projected for future warming overlap with those reconstructed for the Miocene relative to the pre-industrial climate, while plate tectonic configurations were largely similar to modern (Steinthorsdottir et al., 2021; CenCO2PIP, 2023; Herold et al., 2012). Though important oceanic gateway changes occurred, such as the post-Miocene closure of the Panama Seaway (~4 Ma; e.g. Steph et al., 2006; Montes et al., 2012; Sepulchre et al., 2014), and the stepwise closure of the connections between the Mediterranean and Indian Ocean (e.g., Bialik et al., 2019), the Miocene was still more similar in paleogeography to the modern configuration than, for example, other widely studied periods with high atmospheric CO_2 concentrations such as the Eocene (e.g., Burke et al., 2018).

To facilitate use of the Miocene as a potential future climate analogue, well-dated high-quality geochemical proxy records are required. Despite significant recent advances, climate models struggle to achieve the general pattern of higher sea surface temperatures indicated from proxy data (Goldner et al., 2014; Burls et al., 2021; Herbert et al., 2022). Moreover, data coverage is poor in some regions (e.g. North Pacific, Southern Ocean), which further impacts our ability to fully understand crucial aspects of Miocene climate such as latitudinal thermal gradients. To address these issues, multiple recent publications (e.g. The Miocene: the Future of the Past, Paleooceanography and Paleoclimatology Special Issue, 2021), seminars, and workshops (e.g. MioMEET 2019, Stockholm, and MioMEET 2023, Utrecht) have appealed to the paleoclimate and paleooceanography modelling and proxy data communities to synthesize and assess the quality of existing data, and to identify and fill any remaining gaps. Concurrent to the MioOcean proxy data compilation outlined here, there is an equivalent effort to standardize model outputs using consistent Miocene-specific parameters (Burls et al., 2026).

Recent advances in ocean temperature proxy reconstructions, and the extensive spatial and temporal data coverage from sites drilled by the International Ocean Drilling Programme (IODP) and its predecessor programs, provide a timely opportunity to intercalibrate and synthesize Miocene paleotemperature records. Updating, standardizing and integrating all current



95 information enables, amongst other benefits, key insights into the evolution of zonal and meridional temperature gradients during intervals of global warmth or cooling, when major changes in atmospheric CO₂, continental ice volume, and ocean circulation occurred. Standardization of proxy records is also essential to evaluate the role of temperature amongst different mechanisms or forcings in climate sensitivity, and to assess the ability of current generation fully coupled climate models to simulate Miocene climate.

100 This publication focuses on the temperature component of the Miocene ocean. We compile available information from scientific literature into a new open access database (MioOcean) comprising all published Miocene ocean temperature estimates available to date from all applicable proxies and sedimentary archives. Importantly, we revise temperature estimates where required, and update age models to improve site-to-site comparison, both to a state-of-the-art level. In addition to improving model-proxy data intercomparison and furthering our ability to constrain future climate predictions, these updates

105 also provide an improved space for inter-proxy comparison.

1.1 General overview of the Miocene

The Miocene epoch was an extended interval of time including warmer, wetter periods, with reduced polar ice sheets and a lower meridional thermal gradient than today, as well as periods of intense cooling and ice sheet growth (Steinthorsdottir et al., 2021). Though limited evidence of Northern Hemisphere glaciers exists (e.g. Knies and Gaina, 2008), it is generally

110 accepted that they were relatively minor in extent (Steinthorsdottir et al., 2021). The generally warmer climate of the Miocene was also characterised by multiple fundamental transitions, offering the opportunity to investigate the drivers and impacts of change across a wide range of mean background conditions. The Miocene Climatic Optimum (MCO; 16.9–14.7 Ma) is thought to be the warmest phase of the past 35 million years (Steinthorsdottir et al., 2021), accompanied by high levels of atmospheric CO₂ (CenCO2PIP, 2023). Although debate remains about precisely how elevated CO₂ levels were during the MCO, boron

115 isotope reconstructions indicate substantial variability, with shorter-term estimates reaching ~800–1100 ppm (Greenop et al., 2014; recalculated in Sosdian et al., 2018), superimposed on a background CO₂ concentration of ~500 ppm (CenCO2PIP, 2023). Longer-term phytoplankton-based reconstructions similarly span ~300–1100 ppm, while revised calibrations have yielded substantially higher estimates of ~600 to >2000 ppm (Zhang et al., 2013; Stoll et al., 2019; Rae et al., 2021). This range of CO₂ concentrations is similar to the range of possible to probable future climate projections by the International Panel

120 on Climate Change (particularly relevant for AR6 scenarios SSP2, SSP3, and SSP5; IPCC, 2023). Other intervals of interest include the cooling following the MCO, known as the Middle Miocene Climate Transition (MMCT, ~14.7–13.8 Ma), which was characterized by major expansion of Antarctica's ice sheets and falling atmospheric CO₂ concentrations; and the Late Miocene global cooling from ~7 to 5.5 Ma (Shackleton and Kennett, 1975; Flower and Kennett, 1994; Shevenell et al., 2004, 2008; Holbourn et al., 2005, 2013; Herbert et al., 2016; Westerhold et al., 2020; Martinot et al., 2022; CenCO2PIP, 2023;

125 McKay et al., 2025). Despite the relative cooling of the Late Miocene climate compared to the previous intervals of this epoch, reconstructions consistently point to warmer than modern conditions, despite the fact that reconstructed CO₂ concentrations for the late Miocene (~350 ppm; Steinthorsdottir et al., 2021; Brown et al., 2022) are similar to modern (403.35 ppm mean weekly value for last decade <https://gml.noaa.gov/ccgg/trends/weekly.html>; accessed July 2026). Miocene climate events were accompanied by several significant benthic foraminiferal stable isotope shifts, including the Middle Miocene Monterey

130 positive stable carbon isotope ($\delta^{13}\text{C}$) excursion (~16.8–13.6 Ma) and the negative Late Miocene Carbon Isotope Shift (~7.6–6.7 Ma), the sharp $\delta^{18}\text{O}$ decrease at the onset of the MCO (~16.9 Ma), and stepwise $\delta^{18}\text{O}$ increases during glacial expansion of the MMCT (~14.7 and 13.9–13.8 Ma) (Steinthorsdottir et al., 2021). These events are generally recognizable at most locations in the global ocean where sediments contain preserved biogenic carbonate, enabling comparison of records globally and ultimately the generation of a global picture of the climate response.

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1.2 Available proxies and challenges

Over the last several decades, a diverse set of geochemical proxies have been used to reconstruct Miocene surface and deep ocean temperatures. These include inorganic proxies derived from foraminiferal Mg/Ca and $\delta^{18}\text{O}$, clumped isotope composition in carbonates (Δ_{47}), and organic biomarker-based methods including U^{K}_{37} and TEX_{86} . Application and understanding of these proxies has evolved over time. Use of U^{K}_{37} was pioneered in the 1980s (Brassell et al., 1986; Prah and Wakeham, 1987) followed by Mg/Ca paleothermometry, “glassy” (as defined in Pearson et al., 2001) planktic foraminiferal $\delta^{18}\text{O}$ analyses, the TEX_{86} proxy in the early 2000s (e.g. Lear et al. 2000; Schouten et al. 2002; Stewart et al. 2004; Shevenell et al. 2004), and the relatively recent application of clumped isotopes (e.g. Grauel et al., 2013). These paleotemperature reconstructions reveal key features of Miocene climate, including sustained global warmth and a reduced latitudinal temperature gradient during the MCO (Steinthorsdottir et al., 2021 and references therein). However, similar to research undertaken on other past warm climate states like those of the Cretaceous, Eocene, Oligocene, and middle Pliocene, recent efforts as part of the Miocene Climate Model Intercomparison Project (MioMIP), have been unable to reproduce the reduced meridional thermal gradient during the MCO. Reconciliation of this mismatch may require revisiting some model parameterization (e.g., cloud dynamics, ice volume, CO_2) as well as details in the application of temperature proxies (Burls et al. 2021).

For instance, changes in seawater chemistry (e.g. the seawater Mg/Ca ratio and carbonate ion concentration) and preservation of primary trace element/Ca signals need to be considered when converting Mg/Ca to ocean temperature (Gray and Evans, 2019; Tierney et al. 2019). Applying $\delta^{18}\text{O}$ -paleothermometry also requires consideration of preservation state, ensuring foraminifera are ‘glassy’, as well as estimates of the $\delta^{18}\text{O}$ of local seawater (Stewart et al. 2004). The application of U^{K}_{37} has an inherent upper temperature limit due to proxy saturation at $\sim 29^\circ\text{C}$ and still lacks mechanistic understanding of the temperature-proxy relationship (Müller et al. 1998; Herbert, 2003). Uncertainty about the contributing micro-organisms to sedimentary GDGT (glycerol dialkyl glycerol tetraethers) assemblages, which along with near-surface *Nitrososphaerales*, may include deep-dwellers, methanotrophs, or terrestrial producers, may complicate interpretations of the TEX_{86} paleothermometer (Bijl, Sliwinska, et al., 2025; Elling, Inglis, et al., 2026; Hernandez-Sanchez et al., 2014; Zhang et al., 2011; Hopmans et al., 2004). Application of clumped isotope archives necessitates considering the calibrations implemented and the role of diagenesis (e.g. Modestou et al., 2020; Leutert et al., 2020). In addition, comparison of temperatures reconstructed from multiple proxies must include reviewing the underpinning age models of each record, consistent alignment of age models and updating to a common geological time scale (Gradstein et al. 2012, Westerhold et al., 2024). A coordinated effort is needed to bring together the proxy and age model communities to revisit proxy systematics and assumptions and to further explore approaches to reconstruct Miocene ocean temperatures using a multi-proxy approach underpinned by a uniform temporal framework. Integration with the MioMIP effort is critical to identify target time intervals and key compilation outputs.

1.3 Previous compilations and the MioOcean effort

International coordinated ocean temperature compilation efforts have previously focused on understanding climate dynamics in a higher CO_2 world. For instance, DeepMIP focused on the Early Eocene (56 to 48 Ma), a time interval with CO_2 levels of 1000 ppm and global warmth, refining surface ocean and land temperature estimates from an array of proxies in targeted time intervals in conjunction with model intercomparison efforts (Hollis et al. 2019). The PAGES working group PlioVAR focused on one interglacial period during the Pliocene, refining ocean temperature reconstructions from Mg/Ca and U^{K}_{37} proxies (McClymont et al. 2020; 2023). As part of MioMIP, Burls et al. (2021) compiled Miocene ocean temperatures to extract key features for model validation, although individual proxy systematics and/or age models were not reviewed in detail. Building on this MioMIP compilation, the Miocene Temperature Data Portal, a community-driven online platform, houses data repository links (doi.org/10.17043/miocene-temperature-portal-4) to published ocean temperatures from an array of proxies (Lawrence et al. 2021; Sosdian et al. 2024). Recently, the Phantastic effort revisited proxy records from across the Phanerozoic;



due to its gargantuan size, this work focused solely on proxy values rather than the conversion of these values to temperature, and used existing age models (Judd et al. 2022). The MioOcean effort was initiated to focus on Miocene ocean temperatures, providing room to scrutinize the details required for standardization (Modestou and Sosdian, 2023).

MioOcean represents the expansion of the PAGES PlioVAR community framework into the Miocene through the establishment of the PAGES PlioMioVAR Working Group, with MioOcean serving as its Miocene-focused effort to synthesize ocean temperature proxy data (Ford et al. 2022). Initiated in 2022 with 50 members, the international MioOcean effort comprises several working groups, including five proxy-specific groups, an age model group, and a database management group (Fig. 1, Table 1). MioOcean is a multi-year synthesis (2022-current), bringing together a range of scientists with specialist knowledge, and also co-ordinating with the MioMIP modelling community, through regular hybrid and online workshops, and compilation and recalculation of data and ages in sub-divided working groups and individually, coordinated by a steering committee. Working group leads supported data analysis and compilation through additional meetings, alongside regular MioOcean-wide working group meetings. The steering committee met weekly throughout the effort to coordinate and support the team, address scientific hurdles and challenges, and oversee administration and organization. This multi-level coordination facilitated sustained interaction across the community and integration of components.

Here we present the first output from the MioOcean effort, the MioOcean database, which includes a comprehensive temperature compilation and review of proxy systematics for five ocean temperature proxies as well as a critical review and compilation of re-evaluated age models from key sites. To date, this is the most exhaustive Miocene ocean temperature compilation, including 101 publications, 22,941 data points, and records derived from 77 marine drilling sites and 17 onshore drilling and outcrop sites. In this contribution, we review the characteristics and organization of the database and its usefulness for exploring Miocene climate evolution, how proxy data and temperature calculations were revised, and briefly outline continued challenges for refining Miocene ocean temperatures.

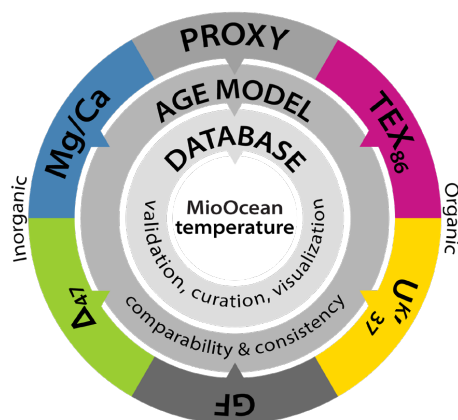


Figure 1. The international MioOcean community effort coordinated 7 working groups including both inorganic (Glassy foraminifera GF- $\delta^{18}\text{O}$, Mg/Ca, Δ_{47}) and organic proxies (TEX₈₆, UK'₃₇), age model, and database management.



Table 1. Key parameters and uncertainties for proxy-specific temperature estimates from MioOcean. Note that for most proxies, uncertainty is dominated by calibration error, and thus the 95 % CI level values essentially represent this parameter.

210 One exception is Δ_{47} , where analytical error dominates and is propagated together with calibration error.

Proxy	Calibration(s) used in MioOcean proxy-specific files	Calibration selected for MioOcean full compilation	Advancement since Hollis et al. (2019)	Uncertainty
Glassy Foraminifera (GF) $\delta^{18}\text{O}$	BAYFOX (Malevich et al., 2019)	BAYFOX (Malevich et al., 2019)	Local and global $\delta^{18}\text{O}_{\text{sw}}$; pH/ CO_3^{2-} effect	$\pm 4.5^\circ\text{C}$ (95 % CI)
Planktic Mg/Ca	Gray and Evans (2019); BAYMAG (Tierney et al., 2019)	Monte Carlo approach using both GE19 variations and BAYMAG	Mg/ Ca_{sw} , pH effect, H-value	$\pm 4^\circ\text{C}$ (95 % CI)
Benthic Mg/Ca	MioOcean Infaunal 1 & 2 calibration; Lear et al. (2015); MioOcean Epifaunal (clean corr and no clean corr, modified after Lo Giudice Capelli et al. (2015))	Infaunal (<i>O. umbonatus</i>): Lear et al., 2015 Epifaunal (<i>C. wuellerstorfi</i>): 'cleancorr MioOcean calibration'	Mg/ Ca_{sw} , CO_3^{2-} effect, H-value	Lear: $\pm 7.1^\circ\text{C}$ (95 % CI) Capelli: $\pm 5.2^\circ\text{C}$ (95 % CI)
Δ_{47}	Foraminifera: Meinicke et al. (2021); Daëron and Vermeesch (2024) Coccolithophores: Clark et al. (2025); Daëron and Vermeesch (2024)	Foraminifera: Meinicke et al. (2021) Coccolithophores: Clark et al. (2025) (consistent with evidence coccolith-specific calibration is required)	Method standardization, analysis of small samples	$\pm 4.0 - 5.6^\circ\text{C}$ (95 % CI) (dependent on analytical errors; this range applies to MioOcean database, may differ elsewhere)
U^{K}_{37}	Müller et al. (1998); BAYSPLINE (Tierney and Tingley, 2018)	Müller et al. 1998	Seasonality, sensitivity at high SSTs	$\pm 3^\circ\text{C}$ (2 standard errors)
TEX ₈₆	Surface calibrations: TEX ₈₆ H, TEX ₈₆ L (Kim et al., 2010), TEX ₈₆ linear (Kim et al., 2010), Global Core Top (Kim et al., 2008; Liu et al. 2009 reciprocal; O'Brien et al. 2017 linear; Varma et al. 2024), Optimal (Dunkley Jones et al. 2020), BAYSPAR SST (Tierney and Tingley, 2014) Subsurface calibrations: Kim et al. 2012 (0–200 m), Ho and Laepple 2016 (100–250 m), BAYSPAR subT (Tierney and Tingley, 2014) Whole water column calibration (He et al., 2021)	Monte Carlo approach (latitude specific): At low/mid latitudes (-40°S to 50°N), TEX ₈₆ H Kim et al. 2010 ($\sigma = \text{RSE} = \pm 2.5^\circ\text{C}$) and BAYSPAR SST ($\sigma = (\text{p84} - \text{p16}) / 2$) At high latitudes ($\geq 50^\circ\text{N}$ or $\leq -40^\circ\text{S}$), BAYSPAR SST and OPTiMAL ($\sigma = \text{OPTiMAL standard deviation}$)	Non-thermal factors, sensitivity at cold SSTs	TEX ₈₆ ^H calibration: standard error (2.5 $^\circ\text{C}$) BAYSPAR calibration: 68 and 95 % CI Optimal calibration: individual standard deviation



2 Methods

2.1 From SST to UOT: defining the temperature represented by marine proxies

215 Prior to summarizing the methods used to convert proxy data to temperature, we first highlight the range of temperatures represented by various proxies, specifically in the depth domain. Though the term *sea surface temperature* (SST) is commonly used to describe the temperature represented by proxies derived from organisms originating in the upper water column, the specific depth at which temperature is recorded is a critical parameter for consideration, particularly when comparing climate model and proxy derived temperatures. Within climate modeling, ‘SST’ often has a more specific meaning, referring to the temperature at the true plane of the sea surface, or very uppermost few meters. Applying the same term to an archive that may represent temperature recorded at a depth below the ocean surface may lead to ambiguity when comparing proxy-derived temperatures with climate model output.

Individual proxies often utilise multiple species; for example, many different foraminifera are suitable for Mg/Ca-based temperature reconstructions. Because each species occupies a distinct ecological niche, the depth at which temperature is recorded relative to the sea surface may differ amongst species, despite belonging to the same proxy type. For organisms such as deep-ocean-dwelling benthic foraminifera, this issue is less relevant; across epifaunal to deep infaunal habitats at any given site, temperature is expected to be constant, and thus MioOcean deems the temperatures derived from the proxies included in our database to be reliable records of *bottom water temperature* (BWT) at that site. Here, BWT refers to the temperature of the immediately above the seafloor at a given location and time, and not specific parcels of ‘bottom waters’ or currents.

230 In contrast to BWT recorders, the temperature recorded by near-surface dwellers is more difficult to constrain because of their dynamic habitat and environment. Plankton-tow sampling shows that planktic foraminifera live and calcify from anywhere near the surface to >500 m water depth, depending on whether they are surface or deep-dwelling species (e.g., Meilland et al., 2019; Yu et al., 2024; Hemleben et al., 1989). A range of calcification depths may also exist within a species, particularly in areas characterised by strong seasonality, or for deep-dwelling species feeding on pelagic snow within their life cycle (e.g. *Globigerina bulloides* calcifies between 0 and 75 m, Osborne et al., 2016; *Globorotalia crassaformis* calcifies between 300 and 500 m, Yu et al., 2024; see Chaabane et al., 2026 for a more thorough overview of literature on this topic). Moreover, foraminifera (and likely other calcifying organisms) have been shown to change their habitat depths over geologic time (Keller, 1985; Boscolo-Galazzo et al., 2021). Phytoplankton, including coccolithophores, are mostly restricted to the sunlit upper part of the ocean but can be found at depths > 100 m, below the mixed layer (e.g. Cortes et al., 2001; Bonomo et al., 2021; Poulton et al., 2017). Archaea produce most GDGTs near the nutricline, typically between ~50 and 250 m water depth, although the exact depth and distribution of production is still debated and may differ from region to region (Sinninghe Damsté et al., 2002; Taylor et al., 2013; Hurley et al., 2018; Rattanasriampaipong et al., 2022; van der Weijst et al., 2022; Rice et al., 2026). Moreover, there is often a seasonal component to each temperature proxy; for example, coccolithophores may bloom in spring in temperate regions (Rosell-Melé and Prah, 2013), while archaea production may occur primarily in the summer in some regions, or spring in high latitudes (Wuchter et al., 2005; Murray et al., 1999). The export depth of GDGTs may also vary seasonally with productivity (Rice et al., 2026). Planktic foraminifera also calcify in different seasons (e.g. Jonkers and Kucera, 2015; Yu et al., 2022; Kim et al., 2023). To complicate matters further, some species used are extinct, meaning their calcification depth is unknown. Finally, the depth of the mixed-layer and thermocline themselves are variable from location to location and may also change seasonally.

250 The paleoceanographic community has developed approaches to constrain apparent calcification depths of planktic foraminifera, or in some cases to tie proxy value to ‘true’ SST (0 m water depth). For example, species-specific apparent calcification depths can be indirectly derived from foraminifera shell chemistry combined with temperature and hydrographic data (e.g., Birch et al., 2012; Stainbank et al., 2019). However, estimates can vary substantially depending on methods and assumptions used for calculations (Stainbank et al., 2019). A complementary approach is to consider the temperature basis of



the proxy calibration itself. Calibrations may be based on temperatures experienced during growth or calcification, as in culture-based calibrations of planktic foraminiferal Mg/Ca (e.g., Gray and Evans, 2019), or may incorporate both culture and core-top observations to establish the relationship between Mg/Ca and environmental temperature, as in BAYMAG (Tierney et al., 2019). Proxy calibrations explicitly tied to SST include $U^{K'}_{37}$ and some versions of TEX_{86} calibrations. Despite progress, there is still some way to go before the temperature depth (and season) recorded by all paleotemperature proxies is fully determined with confidence. Consequently, assigning a specific water depth to every record is currently outside the scope of the MioOcean effort. Thus, we classify proxies derived from organisms commonly considered to represent sea surface temperature (surface-dwelling planktic foraminifera, coccolithophores and archaea) or subsurface temperature (archaea and deeper-dwelling planktic foraminifera) as representing *upper ocean temperature* (UOT). We define UOT as temperature at any depth represented by any upper water column archive. Note that, where calibrations are specifically tied to SST, we also retain this classification. In summary, all inorganic proxies included in the database (planktic foraminifera $\delta^{18}O$, Mg/Ca, and clumped isotopes) are classified as UOT; TEX_{86} may be classified as either SST or UOT depending on calibration used; and $U^{K'}_{37}$ is classed as SST; see following sections for further detail. Further refinement on the temperature range and depth represented by the available proxies will be the focus of subsequent dedicated multi-proxy comparison studies.

2.2 Temperature proxies

Here we present the methodologies used to compile and analyze the ocean temperature data that underpin the MioOcean temperature compilation, including inorganic (glassy planktic foraminifer $\delta^{18}O$, Mg/Ca, and clumped isotopes) and organic ($U^{K'}_{37}$, TEX_{86}) proxy systems. For each proxy, we provide a summary of proxy systematics, calibration choices, and data selection criteria. Companion outputs providing further detail for Mg/Ca, TEX_{86} , and the age model approaches have been published alongside this paper (companion papers in this volume: Sosdian et al., submitted; Drury et al., submitted; Auderset et al., submitted). Temperature uncertainty has been standardized across proxies where possible; for all, uncertainties at 68 % and 95 % confidence intervals, expressed as percentiles of mean temperature (2.5th, 16th, 50th, 84th, 97.5th), have been calculated and are provided in the proxy-specific and multi-proxy compilation (Table 1). For some proxies, this uncertainty is derived from the calibration only ($U^{K'}_{37}$, TEX_{86}); for Δ_{47} , analytical and calibration uncertainties are propagated together; for glassy foraminifera $\delta^{18}O$, the uncertainty in $\delta^{18}O_{\text{seawater}}$ and pH are combined with calibration error; and for Mg/Ca, the sources of error included in the overall uncertainty are calibration-dependent, although for most, several parameters are propagated together (for further detail, see section 2.2.2). The protocols below provide consistent, Miocene-specific frameworks for converting proxy values to ocean temperature.

2.2.1 Glassy planktic foraminifera $\delta^{18}O$ (GF)

The ratio of stable isotopes $^{18}O/^{16}O$ in foraminiferal calcite ($\delta^{18}O$) is the oldest and most widely used marine paleothermometer. It was first discovered by Urey (Urey, 1948) and is based on the temperature-dependent fractionation of the stable isotopes of oxygen between water and the dissolved inorganic carbon species involved in synthesizing biogenic calcite. Briefly, lower water temperatures favour the production of calcite with relatively more ^{18}O . As temperature drops, the difference in vibrational frequency between molecules containing the lighter or heavier isotopes becomes more important in chemical reactions, and consequently, dissolved inorganic carbon (DIC) species preferentially incorporate the heavier isotope (e.g., Pearson, 2012), with $\Delta^{18}O_{\text{DIC-H}_2O} \approx +30 \text{ ‰}$.

The main constraint on the use of $\delta^{18}O$ values as a paleothermometer derives from difficulties in estimating the oxygen isotope composition of seawater ($\delta^{18}O_{\text{seawater}}$), in particular for time intervals older than the Pleistocene (e.g., Shackleton, 1967; Rohling, 2013). The isotopic composition of seawater provides the initial oxygen isotope pool for the biosynthesis of calcite; hence, knowledge of $\delta^{18}O_{\text{seawater}}$ is required to accurately reconstruct temperature, or vice versa. The initial proportion of ^{18}O



295 and ^{16}O , or the heavy versus light oxygen isotopes in seawater, is in turn a product of local salinity (via the control that evaporation versus precipitation exerts on both salinity and $^{18}\text{O}/^{16}\text{O}$) and the global continental storage of ice and groundwater (e.g., Shackleton, 1967; Marchitto et al., 2014; Meckler et al., 2022), both of which can be challenging to reconstruct in the past.

A standard procedure to reconstruct $\delta^{18}\text{O}_{\text{seawater}}$ in the past does not exist, and different studies use different approaches (e.g. Gaskell and Hull, 2023). For the Miocene, recent examples include the combined use of $\delta^{18}\text{O}$ with other paleothermometers independent from $\delta^{18}\text{O}_{\text{seawater}}$ (Leutert et al., 2020; Nairn et al., 2021) or the use of climate models to derive global and local (salinity-derived) $\delta^{18}\text{O}_{\text{seawater}}$ (Boscolo-Galazzo et al., 2021). The latter usually also account for whole-ocean changes in $\delta^{18}\text{O}$ over time (e.g., Gaskell et al., 2022; Boscolo-Galazzo et al., 2025) based on deconvolution of the benthic foraminiferal oxygen isotope stack (Rohling et al., 2022; Miller et al., 2020). In addition, $\delta^{18}\text{O}$ recorded in foraminifera is affected by pH and/or the carbonate ion concentration $[\text{CO}_3^{2-}]$ in the vicinity of the foraminiferal test (e.g., Spero et al., 1997), where lower pH or $[\text{CO}_3^{2-}]$ results in calcite with a more positive oxygen isotopic composition. In the absence of large environmentally driven changes in seawater pH or $[\text{CO}_3^{2-}]$, changes in these parameters are mostly driven by the balance between photosynthesis, respiration, and calcification, all of which impact the carbonate chemistry in the microenvironment around the organism (Spero et al., 1997; Zeebe, 1999; Pearson, 2012).

310 For this compilation, we selected datasets from three published works: Stewart et al. (2004), Boscolo-Galazzo et al. (2021), and Nairn et al. (2021). Following the recommendations outlined in Hollis et al. (2019), our choice was guided by planktic foraminiferal test preservation and we restricted our $\delta^{18}\text{O}$ data compilation to samples minimally altered by recrystallization processes at the seafloor. The datasets from Stewart et al. (2004) and Nairn et al. (2021) are from sediment outcrops in Tanzania and a well (Sunbird-1) located offshore Kenya, respectively. Both locations are renowned for clay-rich sedimentary strata containing exceptionally well preserved or “glassy” foraminifera (GF) (e.g., Pearson et al., 2001; Sexton et al., 2006). The dataset from Boscolo-Galazzo et al. (2021) contains data from several sites with foraminiferal preservation ranging from excellent (glassy) to ‘moderate’. We thus do not use this dataset in its entirety, but limit our selection to the samples with glassy preservation based on the assessment by Boscolo-Galazzo et al. (2021). Besides samples from coastal Tanzania, our selection from that latter paper includes samples from DSDP Site 242 (tropical Indian Ocean) and IODP Site U1482 (northeastern Indian Ocean) which also contain planktic foraminifera assessed as ‘glassy’.

Following the recommendation of Hollis et al. (2019), when data from multiple planktic foraminiferal species in a sample are available, we selected species from the mixed layer based on the depth habitat reconstructions in Boscolo-Galazzo et al. (2021). Specifically, for low-latitude UOT reconstructions in the Miocene, we used species of the genera *Trilobatus* (*T. trilobus*, *T. sacculifer*), *Globigerinoides* (*G. obliquus*, *G. subquadratus*), *Orbulina* (*O. universa*, *O. suturalis*) and *Dentoglobigerina* (*D. altispira*). Where data from different size fractions are available, we selected data from the 300-355 μm size fractions following Birch et al. (2013) and Hollis et al. (2019). For core tops, the use of the 300-355 μm size fraction minimizes deviations from ambient seawater due to photosynthetic symbionts in some species (Spero et al., 1997; Birch et al., 2013), ensuring comparability between datasets.

In order to convert $\delta^{18}\text{O}$ into temperature, we followed the approach of Boscolo-Galazzo et al. (2025). Briefly, we used the method of Gaskell and Hull (2023), which accounts for local and global $\delta^{18}\text{O}_{\text{seawater}}$ (in the former case, informed by oxygen isotope-enabled climate model output), as well as the pH or $[\text{CO}_3^{2-}]$ effect on $\delta^{18}\text{O}$ (Spero et al., 1997). Temperature and uncertainty was derived from $\delta^{18}\text{O}$ using the BAYFOX ‘pooled’ calibration (Malevich et al., 2019) because i) not every species in the compilation presented here is extant and ii) species-specific $\delta^{18}\text{O}$ -temperature calibrations fall within $\sim\pm 1.5^\circ\text{C}$ of each other (Däron and Gray, 2023), which is smaller than the propagated uncertainty calculated here. Long-term global $\delta^{18}\text{O}_{\text{seawater}}$



335 was accounted for using the deconvolution of the benthic foraminiferal $\delta^{18}\text{O}$ stack of Rohling et al. (2022), and we accounted for the relationship between $\delta^{18}\text{O}$ and pH using the mean planktic foraminiferal slope (Spero et al., 1997) and the $[\text{CO}_3^{2-}]$ record of Zeebe and Tyrell (2019). The magnitude of the $[\text{CO}_3^{2-}]$ change since the Middle Miocene ($\sim 50 \mu\text{mol/kg}$) and the mean planktic slope ($-0.0025 \text{‰ per } \mu\text{mol/kg}$) means that the temperatures presented here are insensitive to the choice of $[\text{CO}_3^{2-}]$ record, with the $[\text{CO}_3^{2-}]$ correction resulting in $\delta^{18}\text{O}$ temperatures $\sim 0.5 \text{ °C}$ cooler than they would otherwise be.

340 Likewise, the $\delta^{18}\text{O}$ temperatures we report here are only minimally affected by the choice of the seawater $\delta^{18}\text{O}$ curve used to subtract out the whole ocean change resulting from ice volume and groundwater storage changes. Specifically, using the sea level record of Miller et al. (2020) rather than that of Rohling et al. (2022) would result in Miocene UOT $\sim 0\text{--}2 \text{ °C}$ warmer than reported here. Following Gaskell and Hull (2023), Boscolo-Galazzo et al. (2025) estimated the total uncertainty in UOT reconstructions derived from the combined uncertainty in local and global $\delta^{18}\text{O}_{\text{seawater}}$ and pH for middle Miocene to Recent

345 planktic foraminiferal samples to be on the order of $\pm 5 \text{ °C}$.

2.2.2 Mg/Ca

Mg/Ca paleothermometry is an inorganic proxy based on the relationship between ocean temperature and Mg incorporation into the calcium carbonate (calcite or aragonite) crystal lattice (Clarke et al., 1922; Chave et al., 1954; Chilingar et al., 1962). Modern calibration studies based on culture, core-top, and sediment-trap datasets show planktic foraminiferal Mg/Ca has a ~ 6

350 % temperature sensitivity to water temperature (i.e., $\sim 6 \text{ % increase in Mg/Ca per } \text{°C}$; Gray and Evans, 2019; Tierney et al. 2019). Benthic foraminiferal Mg/Ca has a genus-specific sensitivity to temperature, according to core-top studies. Coupled with $\delta^{18}\text{O}$, Mg/Ca provides important means to examine shifts in ice volume, salinity, and water masses. However, significant additional constraints related to non-thermal controls on foraminiferal Mg/Ca, including sensitivity to pH, salinity, and carbonate ion saturation, as well as changes in seawater Mg/Ca, have complicated the application of Mg/Ca paleothermometry

355 on geological timescales. Nonetheless, application of this proxy has provided insights into upper ocean and bottom water temperature variations on a range of timescales and ocean basins across the Miocene.

The DeepMIP review from Hollis et al. (2019) includes recommendations for converting planktic Mg/Ca to high-confidence temperature estimates, including assessment of preservation using shell weights, correction for non-thermal controls (e.g., salinity and pH), and calibration choice for modern, extant, and extinct planktic Mg/Ca records. Further, they suggested using

360 high-resolution records of changes of the Mg/Ca composition of seawater (Mg/Ca_{sw}) to account for the sensitivity of foraminiferal Mg/Ca (e.g., H-value in more recent calibrations) to these changes. For the MioOcean compilation, we build upon these recommendations and also include methodological considerations for converting benthic Mg/Ca to temperature.

Recent multi-variable calibrations for planktic foraminifera, based on core-top and culture studies, have shown Mg/Ca sensitivity to salinity and pH, although some species have been shown to have no sensitivity to carbonate chemistry (Saenger and Evans, 2019; Gray and Evans, 2019; Tierney et al., 2019). Converting benthic Mg/Ca to BWT can be complicated due to

365 changes of deep ocean carbonate ion saturation state. Infaunal species have been shown to have lower sensitivity to changes in bottom water carbonate saturation state due to the buffering effects in sediment pore water (Mawbey and Lear, 2013; Lear et al., 2015). This contrasts with epifaunal benthic foraminifera, which show a significant sensitivity to saturation in cold, undersaturated waters (e.g., $< 4 \text{ °C}$; $< 25 \mu\text{mol/kg}$; Elderfield et al., 2006). Mg/Ca_{sw} histories derived from a disparate set of

370 proxies show an increase from the Middle Miocene to present, with considerable scatter in the Middle to Late Miocene. Foraminiferal Mg/Ca sensitivity (H-value) to Mg/Ca_{sw} exhibits a range of values for planktic species (0.41–1.00; Delaney et al. 1985; Tierney et al. 2019; Haynes et al. 2023; Boscolo-Galazzo et al. 2025). Due to difficulties in culturing deep-ocean benthic foraminifera, their values of H have been assumed or calculated indirectly for many key species (Lear et al., 2015), with values in a range comparable to that of planktic foraminifera (e.g., Lear et al., 2000, 2015; Segev and Erez, 2006).

375 Here we outline the MioOcean approach, described in detail in Sosdian et al. (submitted) to convert foraminiferal Mg/Ca to temperature based on our current understanding of Mg/Ca proxy systematics and Mg/Ca_{sw} temporal changes. We compiled



Miocene planktic and benthic Mg/Ca records, including associated proxy specific (e.g., size fraction, cleaning method, instrument) and site-specific information (e.g., depositional environment, water depth). In addition, we compiled corresponding preservation assessments from source publications, if available, debased on light microscopy or scanning electron microscope evaluation, and from complementary publications with relevant information (e.g., IODP proceedings and published literature). Hydrographic data derived from GLODAP was extracted from gridded stations nearby to each site to assess modern oceanographic settings. As part of this effort, we reviewed existing Mg/Ca_{sw} records and developed a MioOcean Mg/Ca_{sw} record based on halite fluid inclusions, Na/Ca, calcite veins, echinoderm ossicles, and large benthic foraminiferal records (Lowenstein et al. 2001; Dickson, 2002; Horita et al., 2002; Brennan et al., 2013; Coggon et al., 2010; Rausch et al. 2013; Evans et al., 2018; Zhou et al., 2021; Rosenthal et al., 2022). The compilation is largely based on the dataset of Tierney et al. (2019), with the addition of foraminiferal Na/Ca data used to estimate past seawater [Ca²⁺] and, together with [Mg²⁺] estimates from halite fluid inclusions, derive Mg/Ca_{sw} at higher temporal resolution. We did not include data derived from corals due to the high degree of scatter and also the uncertainty associated with changes in coral reef environment and non-seawater controls (Gothmann et al., 2015; Lebrato et al. 2020).

To convert planktic Mg/Ca to UOT, we applied two multivariable calibrations (Gray and Evans, 2019, from culture experiments and tied to calcification temperature; and Tierney et al., 2019, based on a mixture of core top and culture data, thus also tied at least in part to calcification temperature), which include parameters for sensitivity to temperature, pH, and salinity. We used the MioOcean Mg/Ca_{sw} compilation to account for changes in Mg/Ca_{sw} and an H-value of 0.636, based on a recent compilation of shallow water foraminiferal species (Mucci and Morse, 1983; Evans et al., 2015, 2016b; Holland et al., 2020; Boscolo-Galazzo et al. 2025), to account for the foraminiferal Mg/Ca-Mg/Ca_{sw} sensitivity. Planktic Mg/Ca records are derived from a range of modern (extant) and extinct species. Based on taxonomic and phylogenetic relationships, we applied (1) the modern *Trilobatus sacculifer* calibration to *T. trilobus* and *T. quadrilobatus* and (2) the modern *Globigerina bulloides* calibration to *G. bulloides* records (Aze et al., 2011; Spezzaferri et al., 2018; Boscolo-Galazzo et al. 2025; Lamyman et al., 2026). For extinct species with poorly constrained pH sensitivity, we applied a pooled (multi-species) equation from Gray and Evans (2019), with and without pH correction, to extinct species (*Dentoglobigerina altispira*, *Globoturborotalita pseudopraebulloides*, *Globigerinoides obliquus*, and *Globigerinoides subquadratus*), and a pooled species equation (no pH correction) from Tierney et al. (2019). For *G. subquadratus*, we additionally consider *G. ruber* as a close modern analogue, providing both taxon-specific (Boscolo-Galazzo et al., 2025) and pooled calibration approaches. To account for variations in pH through time, for conversion of pH-sensitive Mg/Ca species records to UOT, we interpolated the compiled boron isotope-based pH record from Whiteford et al. (2024). We note that this presents a lower confidence UOT estimate due to lack of information on site-specific changes in surface ocean pH. We assumed salinity variations play a minor role on calculated temperatures and fall within the uncertainty envelope of calculated temperatures (Sosdian and Lear, 2020).

Bottom water Mg/Ca temperatures were derived from infaunal and epifaunal benthic foraminiferal records. We calculated high confidence BWTs from Mg/Ca ratios of extant and cosmopolitan species, *Oridorsalis umbonatus* and epifaunal *Cibicidoides wuellerstorfi* records. These exhibit relatively limited carbonate chemistry effects while representing complementary infaunal and epifaunal habitats, respectively. Epifaunal Mg/Ca records of the species *Cibicidoides wuellerstorfi* were converted to temperature using a temperature sensitivity based on the Lo Giudice Capelli et al. (2015) core-top compilation, but excluding epifaunal Mg/Ca data from cold, undersaturated waters in the modern ocean and from supersaturated (>80 umol/kg) waters in the northwestern Pacific, due to carbonate ion saturation effects at the low- and high-temperature ends of calibrations (Lear et al., 2002; Elderfield et al., 2006; Yu and Elderfield, 2008; Kubota et al., 2015; Lo Giudice Capelli et al. 2015), and using an H-value of 0.636. For MioOcean, we used three *O. umbonatus* BWT calibrations. First, we use the calibration of Lear et al. (2015), which determines H (0.27) indirectly by using an assumed stable oxygen isotopic composition of seawater (δ¹⁸O_{sw}) in an ice-free climate state. In a similar manner to Lear et al. (2015), we developed 2 new MioOcean calibrations, using clumped isotope BWT as the independent constraint instead of paired Mg/Ca-δ¹⁸O values. For MioOcean 1 we used the generic



temperature sensitivity (0.09; Anand et al. 2003) and calculated an H -value of 0.609. For MioOcean 2, we used the temperature sensitivity from core top study (Lear et al. 2002) and calculated an H -value of 0.838. We compile temperature estimates while accounting for uncertainties in calibration, Mg/Ca_{sw} , H -value, and pH, and report UOT and BWT uncertainties as 68 and 95 % intervals for each calibration scenario.

2.2.3 Carbonate clumped isotopes (Δ_{47})

The inorganic carbonate clumped isotope thermometry relies on the temperature-dependent preferential bonding of multiple heavy rare isotopes in the carbonate mineral lattice, forming isotopologues such as $^{13}C^{18}O^{16}O_2^{2-}$ (Ghosh et al., 2006; Schauble et al., 2006). The Δ_{47} notation represents the ratio of the mass 47 isotopologue ($^{13}C^{18}O^{16}O$) to the mass 44 isotopologue ($^{12}C^{16}O_2$) in the CO_2 liberated from a carbonate mineral by phosphoric acid digestion, normalized to the ratio expected for a stochastic isotope distribution (Wang et al., 2004; Eiler, 2007; Eiler, 2011). The thermodynamic basis of Δ_{47} enables reconstructions of carbonate formation temperature independent of seawater chemistry (Eiler, 2011). This provides a unique opportunity to reconstruct robust temperature records across climate events and transitions, such as the MCO and MMCT, where changes in seawater chemistry occurred that may impact other paleothermometers, such as shifts in ocean water $\delta^{18}O$, Mg/Ca , or pH (Lear et al. 2015; Gray and Evans, 2019; Tierney et al. 2019).

Since the summary of Δ_{47} methods provided in Hollis et al. (2019), there have been three major advances. First, interlaboratory differences have been reduced to levels expected from intralaboratory analytical uncertainties through the establishment of a common carbonate-based reference frame, the Intercarb-Carbon Dioxide Equilibrium Scale (I-CDES), and associated best practice approaches for data acquisition and processing (Bernasconi et al., 2021). Where necessary, datasets compiled within MioOcean have been updated to I-CDES using the conversion equations provided in Bernasconi et al. (2021). Consequently, only those datasets published on I-CDES, or which could be recalculated to I-CDES, have been included (see section 2.2.6 for details of exclusions). Second, for systems capable of measuring very small samples (known as LIDI, or the updated LIDI2, method; Hu et al., 2014; Müller et al., 2017; Oikawa et al., 2024), laboratories are achieving individual replicate measurement masses as small as $\sim 50 \mu g$ (ThermoFisher Kiel IV) or $\sim 120 \mu g$ (Nu Instruments NuCarb), thereby requiring as little as 2-3 mg of clean carbonate to generate a temperature with an analytical precision of approximately $\pm 2 \text{ }^\circ C$ (68 % CI). This ability broadens the scope of possible applications, particularly for monospecific reconstructions dependent on microfossils with infrequent or variable occurrence (e.g. Leutert et al., 2020; Leutert et al., 2021). Third, a better understanding of kinetics and disequilibrium effects on clumped isotope signatures for specific archives has been achieved through the application of dual clumped isotopes (Δ_{47} and Δ_{48} ; Bajnai et al. 2020; Fiebig et al. 2021), although this approach is challenging to apply to foraminifera due to the requirement for much larger sample sizes. A first application to foraminifera suggests that, with a few exceptions, their calcite mostly crystallizes in isotopic equilibrium with seawater temperature (Davies et al., 2026; exceptions include some large benthic foraminifera, which are not widely used in paleoceanographic reconstructions). This finding is in line with recent calibration work, particularly that aligned to I-CDES, showing that many biogenic archives, including foraminifera, agree well with abiogenic carbonate within uncertainty (e.g. Bernasconi et al., 2018; Meinicke et al. 2020; Jautzy et al. 2020; Anderson et al. 2021; Swart et al., 2021; de Winter et al., 2022; Däron and Vermeesch, 2024).

As recent advances have brought published calibrations within uncertainty of each other, the remaining uncertainty for a well-replicated Δ_{47} temperature, combined with a relative scarcity of calibration samples at low temperatures (near $0 \text{ }^\circ C$), leads to difficulty in objectively justifying the selection of one temperature calibration over another. Within the typical ocean temperature range ($0\text{--}30 \text{ }^\circ C$), current Δ_{47} calibrations differ by less than $\sim 2.5 \text{ }^\circ C$ (comparing Anderson et al. 2020; Meinicke et al. 2021; de Winter et al., 2022; the ‘MIT’ and ‘foraminifera’ equations of Däron and Gray, 2023; and Däron and Vermeesch, 2024). Unfortunately, $2.5 \text{ }^\circ C$ is still a large range to consider when employing reconstructed temperature to calculate parameters such as $\delta^{18}O_{seawater}$ or climate sensitivity. Consequently, for foraminifera, we selected options that cover



organism-specific and so-called ‘universal’ approaches (coccolithophores are an exception and are discussed separately below). We used a foraminifer-based calibration (Meinicke et al., 2020) recalculated to I-CDES in Meinicke et al. (2021). This calibration has the advantage of incorporating slightly more data at the low-temperature end, with underlying data measured and calculated in a manner consistent with most Miocene records. Meinicke et al. (2021) is limited to the typical ocean temperature range and employs a York regression (Cantrell, 2008). This is an important consideration, as the expected temperature- Δ_{47} relationship over this shorter, low-temperature range can be approximated by a linear relationship, while a calibration covering the full range of temperatures is not theorized to be linear (Schauble et al., 2006). To represent the ‘universal’ approach and address the issue of non-linearity, we additionally selected the omnivariant generalised least squares (OGLS) regression calibration of Däron and Vermeesch (2024). Those authors compiled most available calibration datasets updatable to I-CDES, including biogenic and abiogenic carbonates, resulting in a dataset that covers a wide temperature range ($\sim 0 - 1000$ °C). Due to its non-linearity, this calibration is not disproportionately influenced by the relatively few high temperature data points included, while incorporating a larger amount of data overall. The choice of either of our two chosen calibrations for foraminifera does not significantly influence relative temperature changes within records. In terms of absolute temperature, for all foraminifera-based records compiled and reprocessed by MioOcean, temperatures derived from these two calibrations are within 1.4 °C, which is well within uncertainty. Both calibrations are also tied to calcification temperature, and thus are classified as UOT.

An important exception to the ‘unified calibration’ hypothesis is apparent for coccolithophores, for which culture- and sediment trap-based calibrations are available (Clark et al., 2024; Clark et al., 2025). Dual clumped isotope analysis indicates coccolithophores are affected by a kinetic bias (Clark et al., 2025), and thus they require a separate calibration; we selected Clark et al.’s (2025) equation 2, which is comprised of the largest amount of coccolithophore-based constraints; this calibration provides the calcification temperature. Since it was necessary to select one temperature for the overall MioOcean compilation, the Clark et al. (2025) calibration is used for coccolithophores; to be consistent with the archive-specific approach, the Meinicke et al. (2021) calibration was selected for foraminifera. However, the unified calibration option is additionally shown in the individual MioOcean proxy files. Note that culture-based Δ_{47} coccolithophore calibrations are tied to calcification temperature, so although components of the same organism are measured by both Δ_{47} and $U^{K'}_{37}$, we classify Δ_{47} based coccolithophore temperatures as UOT (whereas our selected $U^{K'}_{37}$ calibration is regressed directly to SST; see next section). All temperatures and uncertainties have been recalculated from Δ_{47} (I-CDES) values for the proxy compilation, propagating both calibration and analytical uncertainty (Fernandez et al., 2017). For both Meinicke et al. (2021) and Clark et al. (2025), we propagated errors using a Monte Carlo approach (further detail in Appendix A and supplemental tables S1 and S2). For Däron and Vermeesch (2024), we use published code for all calculations, available at <https://github.com/mdaeron/ogls-paper-code>; this omnivariant least squares regression is coupled with Jacobian matrix algebra to propagate uncertainties. Both approaches account for parameter covariance. MioOcean re-calculated uncertainties are very similar, if not identical, across all approaches. For temperatures generated by averaging across multiple adjacent samples, we additionally report a minimum and maximum age denoting the stratigraphic range from which individual Δ_{47} measurements have been pooled; we retained the original publication grouping for this step.

2.2.4 $U^{K'}_{37}$

The $U^{K'}_{37}$ index (Prahl and Wakeham, 1987) is an organic proxy calculated from the relative abundances of C_{37} di- and tri-unsaturated methyl ketones produced by coccolithophores from the family Isochrysidales (see Herbert, 2014 for review). By definition, the index varies between values of 0.0 and 1.0 as the concentrations of the di- and tri-unsaturated ketones, respectively, approach 0.0.

Common methods of calibrating $U^{K'}_{37}$ to temperature use culture experiments (Prahl et al., 1988) or core-top sediments using either linear (Müller et al., 1998) or non-linear (Conte et al., 2006; Tierney and Tingley, 2018) regressions. For the vast majority



of the range of $U^{K'_{37}}$ values (0.0-0.9), these different calibrations are within statistical error of each other. Analytical uncertainties (± 0.15 °C 1σ) are typically an order of magnitude lower than the statistical error of the calibrations (± 1.5 °C 1σ).

Uncertainties for $U^{K'_{37}}$ reconstructions include seasonal biases, particularly at high-latitudes (Rosell-Melé and Prah, 2013; Tierney and Tingley, 2018), effects of sedimentary diagenesis, though likely small (Prah et al., 1989; Teece et al., 1998), and unknown effects of changing producer species over time (Brassell, 2014). Significant amounts of the tetra-unsaturated C_{37} ketone raise the possibility of contributions from sea ice-related haptophytes (Wang et al., 2021), although no Miocene occurrences have been reported. Additionally, the presence of co-eluting compounds can be a source of analytical error in the commonly used gas chromatography-flame ionization detector (GC-FID) method.

A major challenge of applying $U^{K'_{37}}$ is proxy saturation (as $U^{K'_{37}}$ approaches 1.0) at high temperatures, which was particularly prevalent during the globally-warm Miocene. Different calibrations vary on the temperature at which $U^{K'_{37}}$ saturates, with estimates ranging from 28 °C (Prah et al., 1988) to over 30 °C (Tierney and Tingley, 2018 using a Bayesian prior with a standard deviation of 4 °C or greater, see reference for further details) along with higher uncertainty for quantitative SST reconstructions in the warmest range ($U^{K'_{37}} > 0.9$).

Although seasonal alkenone production almost inevitably varies over the ocean, a global sediment trap study found that the $U^{K'_{37}}$ of sinking particles correlates best to mean annual SST (Rosell-Mele and Prah, 2013). For the MioOcean proxy compilation, we have chosen the linear core-top calibration of Müller et al. (1998), which saturates near 29 °C, as the preferred calibration, along with the Bayesian approach of Tierney and Tingley (2018) with a prior of 3 °C as an alternative calibration. We prefer the linearity of the Müller et al. (1998) calibration and favor a more conservative approach that interprets $U^{K'_{37}}$ approaching 1.0 as indicative of mean annual SST greater than 29 °C, without specifying a particular numerical estimate. Extrapolation past the temperature range of modern haptophyte production (29.4 °C in the Tierney and Tingley, 2018 calibration dataset) of the Bayesian approach is unconstrained, so we emphasize the wider uncertainty range, skewed towards the warmer direction, when interpreting absolute SSTs calculated using this calibration in the warm ($U^{K'_{37}} > 0.9$) range. Uncertainties for UOT are provided for 68 and 95 % confidence intervals for each calibration scenario using 1 and 2 standard errors, respectively, of the calibration of Müller et al. (1998) for the linear calibration (1.5 °C) and output values from the Bayesian calibration of Tierney and Tingley (2018). For the calibration of Müller et al. (1998), upper limits of uncertainty above 29 °C are not quantitatively reported, as proxy saturation could reflect any UOT above 29 °C.

2.2.5 TEX₈₆

The TEX₈₆ (TetraEther indeX of 86 carbons) paleothermometer is an organic proxy based on the relative abundance of four GDGTs produced by marine nitrifying archaea of the order *Nitrososphaerales* (formerly *Thaumarchaeota* and *Crenarchaeota*), and it is defined as an index (Schouten et al., 2002). Both a quasi-global surface-sediment dataset and culture experiments indicate that these archaea incorporate an increasing number of cyclopentane rings into their GDGTs as a function of increasing temperature (Schouten et al., 2002; Elling et al., 2015). Analytical errors are typically small (< 0.3 °C), but calibration errors are substantial (several °C; see MioTEX companion paper Auderset et al., submitted). Important issues in the application of TEX₈₆ as an ocean temperature proxy are 1) non-thermal influences on TEX₈₆, 2) the wide range of water depths at which GDGTs are produced, and 3) the fit of the calibration between temperature and TEX₈₆.

The impact of these confounding factors is at least partly addressed using commonly discussed and applied GDGT indices in the community. These include the Branched versus Isoprenoid Tetraether (BIT) index (Hopmans et al., 2004), the methane index (MI) (Zhang et al., 2011), GDGT-2/crenarchaeol ratios (Weijers et al., 2011), GDGT-0/crenarchaeol ratios (Blaga et al., 2009), %GDGT-0 (Sinninghe Damsté et al., 2012), GDGT-2/GDGT-3 ratios (Taylor et al., 2013, Hernandez-Sanches et al. 2014), and the Δ Ring Index (Zhang et al., 2016). For a detailed discussion of each index and the screening criteria applied



in this proxy compilation, we refer the reader to the MioTEX companion paper (Auderset et al., submitted) and other recent reviews (Bijl, Sliwinska, et al., 2025; Elling, Inglis, et al., 2026). GDGTs are dominantly produced near the nutricline, typically between ~50-250 m water depth (e.g., Sinninghe Damsté et al., 2002). GDGTs from below ~150-200 m are produced by a different clade than those produced at shallower depths (Taylor et al., 2013; Hurley et al., 2018; Rattanasriampaipong et al., 2022). Sedimentary TEX₈₆ distributions dominantly reflect temperature variability of the shallow subsurface (SubT), just below the mixed-layer. Because SubT variability at this depth strongly correlates to SST, TEX₈₆ is widely regarded as a proxy for SST as well (Ho and Laepple, 2016; Van der Weijst et al., 2022). The origin depth of sedimentary GDGTs has been widely debated (Schouten et al., 2002; Taylor et al., 2013; Tierney and Tingley, 2014; Ho and Laepple, 2016; Hurley et al., 2018; Rattanasriampaipong et al., 2022; van der Weijst et al., 2022), resulting in various calibrations for converting TEX₈₆ to temperature and development of additional indices (e.g. GDGT-2/GDGT-3, see Taylor et al. 2013) for tracing the depth of origin for GDGTs. The dominant depth of GDGT origin is important because the range of ocean temperature decreases with depth, affecting the slope of the proxy response as reflected in surface sediments, and therefore the magnitude of recorded temperature range in the paleodomain (Ho and Laepple, 2015). Several studies calibrated TEX₈₆ to SST as well as temperature at 100 m depth (Schouten et al., 2002) and integrated 0-200 m depth (Kim et al., 2008, 2010; Tierney and Tingley, 2014). However, because GDGTs are scarce in the mixed-layer, some studies suggested a deeper upper limit (Hurley et al., 2018; Sinninghe Damsté et al., 2002), as deep as 100-250 (Fokkema et al., 2024) or 100-350 m (van der Weijst et al., 2022), depending on GDGT contributions from the deeper clade. Sedimentary TEX₈₆ values almost linearly correlate to SST in the range of ~10 to ~27 °C in the modern ocean (e.g., Schouten et al., 2002; Tierney and Tingley, 2014). The proxy response is lower or even absent below 10 °C, which makes it challenging to use TEX₈₆ in colder basins. For colder environments, inclusion of OH-GDGTs in the TEX₈₆ equation is a promising solution (Varma et al., 2024). Calibration for TEX₈₆ values beyond modern surface sediments (e.g. for past warm climates) is also unlikely to be linear (e.g., Fokkema et al., 2024), but the shape of the calibration beyond the modern ocean range is currently the subject of active research. Acknowledging the latest discussions on GDGTs depth of production and TEX₈₆ calibrations, we use a multifaceted approach to reconstruct TEX₈₆-derived SST or UOT. For high-temperature reconstructions at low latitudes, we apply TEX₈₆^H by Kim et al. (2010) and the Bayesian model BAYSPAR SST (Tierney and Tingley, 2014). For high-latitude regions and lower temperatures, we use the machine-learning-based OPTiMAL calibration (Dunkley Jones et al., 2020) and BAYSPAR SST. Because the origin of the GDGT-temperature signal is not fully understood, we also report subsurface temperature reconstructions for each core site. We use a depth-integrated approach covering ranges from 100 to 250 m by Ho and Laepple (2016) and 0 to 200 m by Kim et al. 2012 in combination with the BAYSPAR subT calibration (Tierney and Tingley, 2014). This approach reflects the debated production depths of GDGTs and acknowledges the strong correlation between subsurface temperature and SST variability. With this comprehensive approach, we adapt the use of the TEX₈₆ proxy to regional and depth-related production variability. More information regarding the various calibrations, special considerations for data interpretation, and regional differences can be found in the MioTEX companion paper (Auderset et al., submitted).

2.2.6 Excluded and limited records

Compiled records derive from Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP), Integrated Ocean Drilling Program (Integrated ODP; 2003-2013), International Ocean Discovery Program (International ODP; 2013-2024), onshore drilling sites and outcrop locations that were marine during the Miocene but are now exposed on land. Some existing Miocene ocean temperature records were unable to be incorporated into the MioOcean database; the reasons for these exclusions are listed here. For GF, as discussed in section 2.2.1, the criteria for this proxy was to only include records derived from planktic foraminifera considered ‘glassy’, and thus only a limited number of records were selected for incorporation to the database. For Mg/Ca, the dataset from ODP Site 747 (Verducci et al., 2007) could not be fully incorporated because the Mg/Ca data are



not available from a repository. For the onshore LOM-1 site, we compiled Mg/Ca data from both planktic and benthic species but did not convert these data to temperature due to lack of age model constraints (Scheiner et al., 2018). For Δ_{47} , one record was excluded (IODP Site U1338; Drury et al., 2016), as underlying data could not be reprocessed to the I-CDES reference frame. That data was produced before I-CDES was devised, and unfortunately without the requisite standards in the original analytical sequence. Two excluded U^{K}_{37} records are from ODP Site 1148 (Mercer and Zhao, 2004) and IODP Site U1425 (Wittkopp, 2017), due to missing or erroneous reporting of sample information. U^{K}_{37} data from Site U1338 (Rousselle et al., 2013) are included, but with only published ages; this record does not have a MioOcean Age due to incomplete sample information, which prohibited the prior step of checking and reconstructing depth. TEX_{86} data from ODP Site 747 and IODP Site U1425 (Wittkopp, 2017) were excluded due to data retraction by authors.

2.3 Age models

2.3.1 Chronological approaches and geological timescales

Accurate age models are essential for interpreting the timing and sequence of geological and climatic events. The MioOcean database incorporates a compilation of age models developed using a range of chronological approaches (Table 2), including biostratigraphy, magnetostratigraphy, chemostratigraphy, radiometric dating, and astrochronology. Biostratigraphy utilises the calibrated evolutionary first and last occurrences and abundance changes of marine microfossils, whereas magnetostratigraphy relies on calibrated reversals in the polarity of Earth's magnetic field. Chemostratigraphy correlates geochemical proxy records to a calibrated reference section, whereas radiometric dating provides absolute ages using the decay of radioactive isotopes. Astrochronology correlates cyclicity driven by variability in the Earth's orbit (e.g. Milankovitch-driven) in geological records (including elemental data and stable isotopic records) to a known astronomical solution or astronomically calibrated reference section. In many cases, age models are constructed using a combination of these approaches, integrating multiple lines of chronological evidence to improve age control and stratigraphic consistency. Each method has strengths and limitations, summarized in Table 2. For example, biostratigraphy provides broad estimates with global geographical spread, but its precision can be affected by diachronous (dis)appearances, ecological exclusions, or variable preservation (e.g., dissolution of carbonate/siliceous/organic-walled fossils); astrochronology can provide highly accurate age models but requires continuous sequences and clear orbital signals.

Table 2. Summary of the principal chronological disciplines used to constrain the age models from key sites that were revisited and included in the MioOcean age model compilation. The table outlines the underlying principle of each chronology type, together with its main advantages and limitations, and the number of MioOcean age models that (partially) incorporate each approach. Individual age models may employ multiple chronological methods in combination to improve age control and correlation.

Chronology type and associated MioOcean age model category	Principle	Main advantages	Main limitations	MioOcean age models using chronology type
Biostratigraphy (B)	Fossil datums	Widely applicable, global coverage with different fossil groups	Diachroneity, preservation effects	28
Magnetostratigraphy (M)	Polarity reversals	Global correlation	Requires preservation of magnetic signal, constant sedimentation rate and biostratigraphy to identify which reversal	17
Chemostratigraphy (included within +)	Geochemical correlations	Useful for major excursions	Dependent on reference record	8 (within +)
Radiometric dating (included within +)	Radioactive decay	Independently constrained numerical ages	Limited availability in marine sediments	8 (within +)
Astrochronology (A)	Astronomical tuning	Highest precision	Requires continuous records with well-defined cyclicity	15



Chronologies are most effective when combined to form an integrated stratigraphy (Hilgen et al., 2015, Sinnesael et al., 2019).
 For example, numerical approaches (i.e., radiometric dating, astrochronology) provide a way of calibrating relative approaches
 (i.e., biostratigraphy, magnetostratigraphy) to absolute ages. These calibrations are combined to form the Geologic Time scale
 (GTS), which is regularly updated to incorporate ongoing chronological research. The most recent GTS publication is
 Gradstein et al. 2020, however, the MioOcean Age Framework is anchored to GTS2012 (Hilgen et al., 2012; for details, see
 section 2.2.4, and Drury et al., submitted).

2.3.2 Challenges and rationale for developing a consistent MioOcean age framework

Age models and GTSs are dynamic and continue to evolve over time (Gradstein et al., 2020, Westerhold et al., 2024, 2026).
 This means that datasets from the same location cannot be automatically compared if they use different chronologies or GTS.
 This is a real concern for MioOcean: five international GTSs have been produced since the compilation's earliest dataset was
 published in 1998 (Herbert and Schuffert, 1998), so the data assembled here are anchored to a range of different timescales,
 leading to potential age offsets. For example, using magnetic reversals calibrated with the Cande and Kent (1995) timescale
 will result in a different age model than if the same reversals are calibrated to GTS2020 (e.g., T C6Bn.1n is 782 kyr older in
 Cande and Kent (1995) compared to Raffi et al. (2020)). Age model development is also highly iterative, which means that
 the chronology underpinning individual proxy records may quickly become outdated. Finally, for material recovered by the
 IODP and its predecessor/successor programmes, the depth scale itself is also a model, which when revised can also impact
 the depth-age relationships of age models (Drury et al., 2026).

2.3.3 The MioOcean age framework and the MioOcean age model compilation

The ultimate aim was to achieve a consistent age framework for the MioOcean proxy compilation and overall MioOcean
 database and to provide as accurate as feasible chronologies that allow for reliable regional comparisons and the identification
 of genuine climatic patterns across space and time. To accomplish this, the MioOcean proxy data and chronologies need to
 utilise a coherent depth and age model at each location, linked to a consistent timescale and harmonised into the MioOcean
 age model compilation. Drury et al. (submitted) provide further discussion of the MioOcean age framework, age model
 compilation and the reliability of the age models contained within it. Changes between the originally published ages and the
 new MioOcean ages for the UOT and BWT proxy records is also discussed there.

A survey of the age models used for existing Miocene temperature records revealed a diversity of approaches, with different
 geological timescales also being applied (Drury et al., submitted). The survey demonstrated that datasets from the same site
 rarely utilised the same or most recent depth/age model available. To realise a consistent MioOcean age framework, many
 sites required critical revision of sample metadata to enable accurate updating of both the depth and age models. Due to the
 scale of the revision and verification required, 38 sites were prioritised. These key sites were identified by the proxy groups,
 based on the number of proxies, total data points, and geographical and temporal coverage (for further detail, see Appendix,
 Table B1). Additionally, GTS2012 was chosen as the baseline timescale for the MioOcean age framework due to its widespread
 use amongst MioOcean key sites and compatibility with astrochronology (Hilgen et al., 2012). For non-key sites, MioOcean
 temperature records are currently presented using their original published age models in the “MioOcean recommended age”.
 The workflow developed as part of the MioOcean effort provides a framework that can be applied to additional sites and time
 periods in future studies.

To achieve a consistent MioOcean age framework, a structured workflow was developed to verify, standardise, and revise the
 depth-age models for key sites and present them in the MioOcean age model database. For all key sites, depth-age model
 information was collated in a consistent, standardised, and harmonised format, and with depth-scale-verification to ensure that



the most recent depth model was consistently applied to all tie points. Age models requiring this verification and standardisation step only were assigned the status ‘MioOcean – Verified and Standardised’. The age models at some key sites required additional revision and were categorised as ‘MioOcean – Revised, Verified, Standardised. The revision process involved (1) ensuring the most recent stratigraphic information (e.g., biostratigraphic datums, reversals, chemostratigraphic events) were assigned GTS2012 ages and (2) integrating stratigraphic information from multiple sources to generate a new age model and/or critically evaluating previously compiled age models, potentially adding or removing ties if needed. The MioOcean age models were then applied to the depth-checked proxy compilation, resulting in a range of age changes (summarized in Appendix, Table B1). Standardised MioOcean database structures, calculation workflows, and reproducible templates and code for depth scale conversion (from sample ID to primary depth (e.g., mbsf) and then (adjusted) composite depth), and depth-age modelling facilitated this process. All MioOcean age models are presented in the MioOcean age model compilation, summarising sample ID, depth information (original and recalculated where possible), stratigraphic information (biostratigraphic, magnetostratigraphic, and tuning tie-points), GTS2012 age, and age model metadata (Drury et al., submitted).

Constraining the reliability and associated uncertainty of individual age models is challenging due to the diverse chronological approaches utilised in the compiled MioOcean dataset. It is not yet possible to place a realistic, absolute uncertainty that encompasses the true complexity affecting each chronological approach. We therefore developed a reliability grid for each age model type, which assessed both data reporting and age model quality (Drury et al., submitted). These age model-specific assessments were then combined into an integrated site-specific reliability grid providing overall guidance on age model reliability for each key site (key sites that have intervals with distinct age model categories have their own reliability indicator key).

2.3.4 Guidelines and scope for future work

Guidelines for archiving and updating depth-age models are provided here to facilitate future research. One critical point is that full sample identification (ID) information should always be provided for all depth-age tie points and proxy data upon publication. Full sample ID (e.g., including Site, Hole, Core, Section, and interval depth information) is especially crucial for scientific ocean drilling samples where multiple depth models can exist (e.g., Drury et al., 2026). Additionally, depth model type and source information should be reported to ensure future reproducibility. For non-ocean drilling samples, as much sample metadata should be provided as possible as this can only benefit future integration and updates. Finally, we recommend adopting standardised and harmonised age model compilation structures and reproducible workflows for depth-age model calculations, which facilitate continuous updates of depth and age models and proxy data alike as new information becomes available.

Despite the advancements and formulation of a consistent MioOcean age framework, challenges remain. This includes the extended ~18 Myr timespan of the Miocene, incomplete records due to sedimentological gaps and carbonate dissolution events, and the need for better synchronization of biostratigraphic, magnetostratigraphic, and astrochronological constraints (see Drury et al., (submitted) for further detail). Beyond MioOcean, future efforts should focus on extending comparable chronological harmonisation to records that span intervals outside the Miocene and on developing community frameworks for the continuous updating and stewardship of age models. Such efforts could contribute to broader initiatives, including Time Integrated Matrix for Earth Sciences (TIMES, Westerhold et al., 2024), aimed at improving the consistency, transparency, and interoperability of paleoclimate datasets across geological timescales. Our age model compilation enables us to highlight well-dated sites with excellent chronologies (e.g., continuous astrochronologies) that are ideal targets for further study. We also identify well-studied sites with excellent proxy datasets but comparatively low-confidence age models, where improved chronologies would substantially enhance their value for regional and global syntheses.



2.4 Data

2.4.1 Data compilation (proxy and ages) and sources

To build the MioOcean temperature compilation, we compiled all published Miocene proxy data used to reconstruct upper and bottom ocean temperature, from both organic (U^{K}_{37} and TEX_{86}) and inorganic (Mg/Ca, $\delta^{18}O$, and Δ_{47}) proxies (Fig. 1, 2).

705 Compiled records derive from Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP), Integrated Ocean Drilling Program (Integrated ODP; 2003-2013), International Ocean Discovery Program (International ODP; 2013-2024), onshore drilling sites and outcrop locations that were marine during the Miocene but are now exposed on land (Fig. 3). The datasets cover all major ocean basins, encompass a range of water depths and latitudes and are the most complete compilation of Miocene ocean temperature proxy data currently available. A list of compiled core sites and publications is provided in
 710 Supplementary Table S3. All collected datasets were systematically organised in proxy-specific worksheet templates to facilitate consistency.

The data incorporated into the MioOcean proxy compilation originate from a variety of sources, primarily peer-reviewed journal articles accompanied by datasets stored in open access data repositories (such as Pangaea, EarthChem, NOAA, Zenodo, Miocene data portal); where necessary, clarifications or required sample identification information, such as full IODP core
 715 sample information, were derived from personal communications with authors. We found the latter information lacking more often in older sources, but occasionally also in more recent publications; for traceability, all sample information required to trace a specific sample back to its origins was required in order for data to be included in the proxy compilation.

To place the compiled proxy records on a common temporal framework, we compiled and, where necessary, revised the depth and age models of selected MioOcean sites. As with the proxy data, all depth and age information was systematically organised
 720 using standardised templates and reproducible R scripts for depth-scale conversion (sample ID, mbsf, composite depth) and depth-age modelling, and harmonised into the MioAge compilation to ensure consistency across sites (Drury et al., submitted). The depth and age model information originate primarily from the original peer-reviewed publications and their associated repositories, supplemented by revised composite depth scales (e.g., Wilkens et al., 2013, 2017; Kochhann et al., 2016), GTS2012 calibration sources for biostratigraphic and magnetostratigraphic datums (Anthonissen and Ogg, 2012; Ogg, 2012;
 725 Hilgen et al., 2012), and orbital solutions for astronomically tuned records (Laskar et al., 2004, 2011). Where full sample identifiers or depth-scale details were missing, these were obtained through personal communication with the original authors or, where possible, recovered from core repository databases (e.g., Site 154). As for the proxy data, full sample information allowing a datum or sample to be traced back to its origin was required for a site's age model to be included in the compilation.

2.4.2 Database quality control

730 To ensure the quality and consistency of the MioOcean database, we implemented a rigorous quality control process. We used both automated and manual checks to identify and correct potential errors derived from this data compilation step and inaccuracies in the original datasets. Where possible, MioOcean recalculations were performed using standardised code to minimise human error and ensure reproducibility. Identifiers for each data point were created by generating a hash from a subset of columns that contained key sampling and proxy information. The hashes were later used to check these data for
 735 duplicates and merge newly calculated depths and ages from the age model group. Finally, the database was cross-checked with original publications to confirm the accuracy of the extracted data.

2.4.3 Paleolatitude and paleolongitude calculations

To be consistent with the ongoing MioMIP efforts, specifically to improve database usability for the Miocene climate modelling community, paleolatitudes and paleolongitudes for each sample locality were calculated using the GPlately Python
 740 library (Mather et al., 2023) and the plate tectonic reconstruction model of Zahirovic et al. (2022), accessed via the



PlateModelManager package (part of the GPlately Python package). For each sample, the modern site coordinates were rotated back to their paleoposition at the ‘MioOcean recommended age’ using the GPlates plate reconstruction framework, anchored to the Africa plate (plate ID 701701).

2.4.4 MioOcean recommended upper ocean temperature and bottom water temperatures

To provide a consistent basis for multi-proxy and model-data comparisons, we define a set of recommended UOT and BWT estimates recalculated from raw proxy values using a standardised set of calibrations. These estimates provide the recommended MioOcean temperature data product rather than relying on temperatures reported in the original publications. Where multiple calibrations exist for a given proxy, we selected those most appropriate for Miocene boundary conditions and the geographic and thermal range of the compiled sites, as discussed in the proxy-specific sections above (sections 2.1 and 2.2) and detailed in the MioTEX and MioMG companion papers (Auderset et al., submitted; Sosdian et al., submitted). For glassy foraminifera, MioOcean UOT estimates are calculated using the BAYFOX ‘pooled’ calibration (Malevich et al., 2019). For Δ_{47} MioOcean UOT estimates, for temperatures derived from coccolithophores, Clark et al. (2025) was used; where UOT or BWT were derived from foraminifera, Meinicke et al. (2021) was selected (although as discussed above, this choice was primarily for consistency, as the Daëron and Vermeesh (2024) calibration is equally valid). For $U^{K'_{37}}$, the global core-top SST calibration by Müller et al. (1998) was implemented. For Mg/Ca MioOcean UOT, we calculated temperatures using a Monte Carlo ensemble approach ($N = 10,000$ draws) using UOT scenarios from (1) both variants of Gray and Evans, (2019) and (2) BAYMAG, assuming an Ω value of 5 (no dissolution correction). For the Mg/Ca MioOcean BWT we utilized “MioOcean 2” for infaunal scenarios (only *O. umbonatus*), based on narrower uncertainty envelopes and temperature sensitivity derived from Lear et al. (2002), and “bwt epifaunal cleancorr” for epifaunal scenarios (only *C. wuellerstorfi*). For TEX₈₆, we calculated a Monte Carlo SST ensemble ($N = 10,000$ draws) using calibrations selected by latitude. At low latitudes (-40°S to 50°N), TEX_{86H} (Kim et al. 2010) ($\sigma = \text{RSE} = \pm 2.5^\circ\text{C}$) and BAYSPAR SST (after Tierney and Tingley, 2014) ($\sigma = (p_{84} - p_{16}) / 2$) were used with equal weight. For BAYSPAR we used the calculated paleolatitude and paleolongitude as described in Section 2.3.3. At high latitudes ($\geq 50^\circ\text{N}$ or $\leq -40^\circ\text{S}$), BAYSPAR SST and OPTiMAL ($\sigma = \text{OPTiMAL standard deviation}$) were used with equal weight. Where a calibration was unavailable for an individual sample, it was excluded and the remaining calibration carries full weight for that row. Ensemble percentiles are collapsed across both calibrations and all draws simultaneously. All MioOcean temperatures are reported at standard percentile levels (2.5th, 16th, 50th, 84th, 97.5th), with uncertainties derived as described in section 2.2, and summarized in Table 1.

2.4.5 MioOcean recommended age

In the proxy-specific and multi-proxy compilation, both the published (for all sites) and MioOcean ages (for key sites) are provided (columns “Published age (Ma)” and “MioOcean age (Ma)”). Additionally, the column MioOcean recommended age (Ma) is provided, including the MioOcean ages (Ma) for the 38 key sites with MioOcean age models and also published ages from those sites not included in the update. For key sites, MioOcean recommended age (Ma) is blank for a handful of datapoints where the sample ID was incomplete and no MioOcean depth could be calculated. We recommend that this data is not plotted on originally published age as this will not/may not be consistent with the MioOcean age calculated for this site. For key sites where the MioOcean age model did not cover the full extent of the published data (e.g., non-Miocene intervals), the MioOcean recommended age (Ma) column reports Published age (Ma). For users working across these transitional intervals, be aware that age reversals occur in a handful of places (see Drury et al., (submitted) for details).

2.4.6 Data management and storage

We used Python-based scripts for data validation, processing, and compilation to automate the process of recalculating MioOcean temperature records, thereby minimizing errors and ensuring consistency across the dataset. For traceability and



reproducibility, all Python code used for the validation and compilation of the MioOcean temperature and age model compilation is publicly available on GitHub (https://github.com/audersea/mio_compilation). The MioOcean database, including both the temperature and age model compilations, is version-controlled and hosted on Zenodo (doi: 10.5281/zenodo.22258386), where it is publicly available for download. The Zenodo link provides access to the most recent version of the database, which is continuously updated as new data or corrections become available.

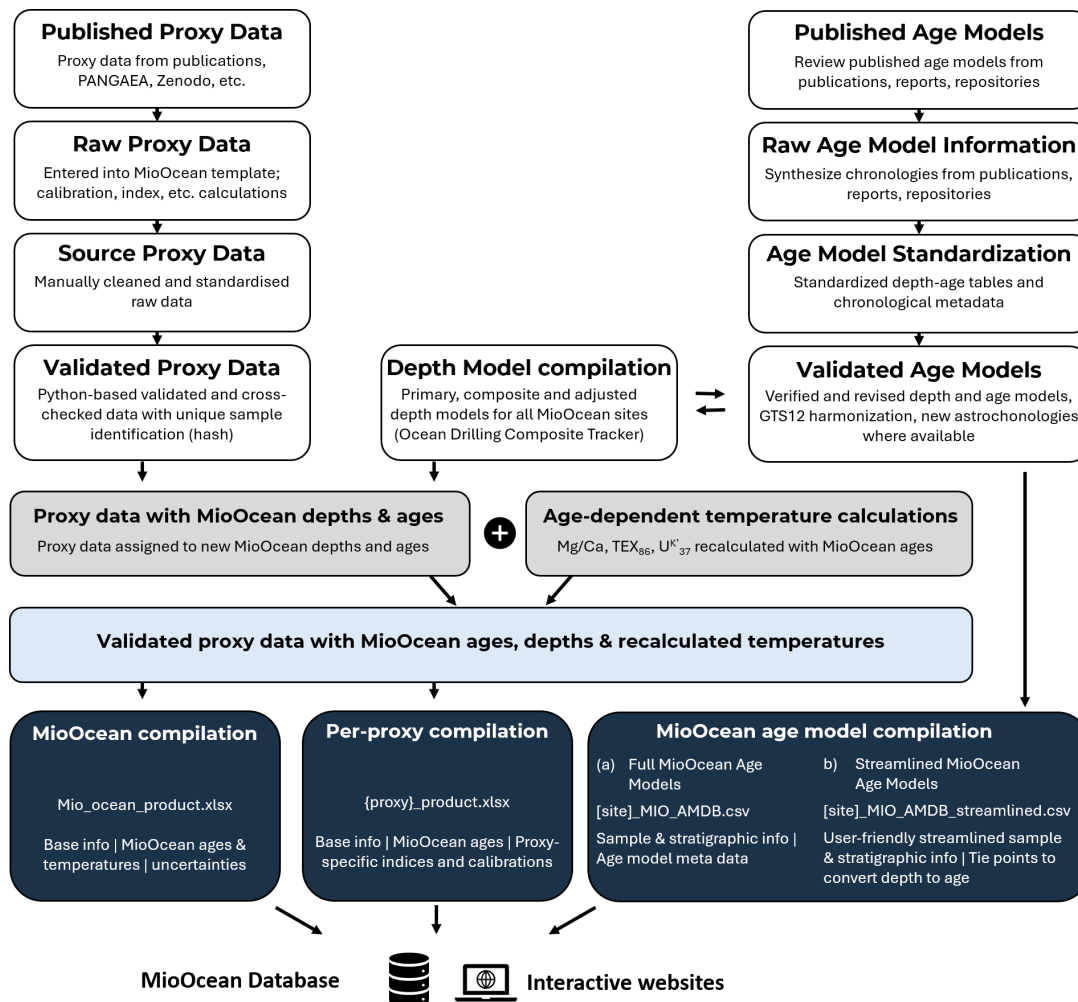


Figure 2. Workflow for data processing. The pipeline starts with collating relevant publications, transferring these into unstandardized raw data in bespoke templates, before manual standardization into 'source data' followed by automated validation steps producing 'validated data'. Concurrently, published age models are compiled, harmonized, and revised to derive an internally consistent set of new MioOcean age models, while published calibrations are compiled to recalculate proxy temperatures with associated uncertainty. A major feature of the database is the use of automated data assimilation scripts to merge these datasets, using unique hash identifiers. The final step is separation into data products: the MioOcean compilation, per-proxy compilations, and per-site MioOcean age models, which together populate the MioOcean Database and interactive website. The Ocean Drilling Composite Tracker tool (Pälike and Westerhold, 2025) can be found at <https://doi.org/10.5281/zenodo.17158096>.

2.4.7 Data visualisation

MioOcean has a strong focus on making the database accessible to all users. To facilitate interaction and exploration, we have developed a Python-based Streamlit dashboard, which can be accessed through our website (<https://www.mioocean.com>). The MioOcean Streamlit dashboard allows users to explore the temperature records and age data through a set of subpages with



800 geographical maps, scatter plots, histograms, and other dynamic visualization formats. Users can display and filter data by
 adjusting parameters such as temperature calibrations, proxy types, and specific geographic regions or time intervals and
 instantly visualise the outcomes of these adjustments. The Streamlit dashboard is directly linked to the latest data compilation
 files stored on Zenodo, allowing for continuous updates and adjustments as new data becomes available or as user needs
 evolve. These platforms and regular updates ensure the MioOcean database will remain an up-to-date resource for the scientific
 805 community.

2.4.8 MioOcean temperature and age model compilation structure

The database contains three separate compilations:

The **proxy-specific compilation** files (tex86_product.xlsx, uk37_product.xlsx, mgca_product.xlsx, d47_product.xlsx,
 d47_replicates_product.xlsx, gf_product.xlsx) contain the full suite of calibration outputs, raw and standardised proxy
 810 measurements, age model information and all associated metadata. Each file is structured into three tabs: Data, containing all
 sample-level measurements, calibration outputs and age model information; Columns, providing a description of each column
 name and data type; and Metadata, recording provenance information including compilation date, input file hash, and git
 commit. These files are designed for users requiring detailed, proxy-level information, such as those who wish to explore
 alternative calibrations or conduct proxy-specific analyses.

815 The **multi-proxy compilation** (mio_ocean_product.xlsx) follows the same three-tab structure and is a reduced version that
 retains a single recommended calibration per proxy, and in some cases combines calibrations using a Monte Carlo ensemble
 approach, to provide a consistent and comparable dataset for each of the five proxies. Similar to the proxy-specific files, this
 file also contains all the age model information. This file is designed for applications such as climate model benchmarking and
 global mean surface temperature reconstructions. Calibration equations, input parameters, and uncertainty treatment for this
 820 multi-proxy compilation are summarised in Table 1.

The **age model compilation** files from the 38 newly developed age models by the MioOcean age model group are provided
 as per-site CSV files following the naming convention _MIO_AMDB.csv (e.g., 982_MIO_AMDB.csv,
 U1338_MIO_AMDB.csv), and are distributed in two versions suited to different user needs. The full age model compilation
 (01_MioOceanAMDB_Full/) is intended for stratigraphers and age model specialists. Each file contains the complete set of
 825 tie points used to construct the age model, including depth information in multiple depth scales (MBSF, MCD, RMCD,
 ARMCD), splice status, tie point type (biostratigraphic, magnetostratigraphic, or orbital tuning), event names and their original
 published equivalents, age assignments in Ma with associated uncertainties and uncertainty notes, age category quality flags,
 interpolated sedimentation rates, and age model status flags. The streamlined version (02_MioOceanAMDB_Reduced/) is
 designed for researchers who wish to apply MioOcean age models as new data is produced. Each per-site file retains only the
 830 columns required for depth-to-age interpolation along with key source information. This includes tie type, sample ID, depth,
 and age, making it straightforward to assign MioOcean ages to any sample with a known equivalent (composite) depth at a
 given site. One critical requirement for correct application of MioOcean ages is that new data must be assigned depths along
 the same splice model, where a splice is used.

3 Results

835 3.1 Spatial and temporal temperature data coverage

The MioOcean dataset includes 94 unique sites globally, five temperature proxies and a total of 22,941 data points drawn from
 101 reference publications, providing a robust multi-proxy record over a broad spatial and temporal range. Figures 3 and 4
 show the spatial, latitudinal, and temporal distribution of MioOcean proxy data across the last 25 Ma.



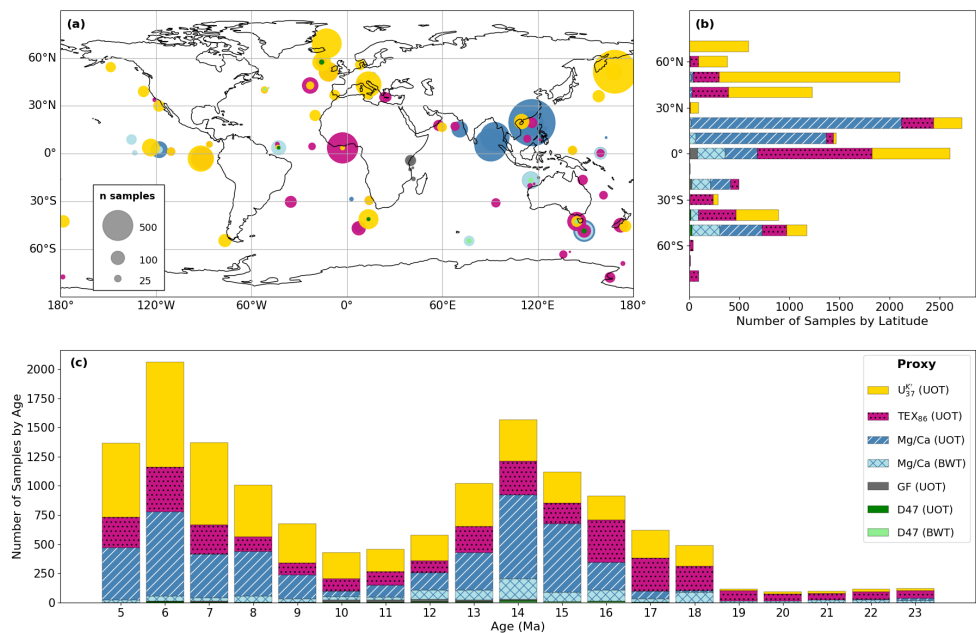
Spatially, sites with the largest amount of data are clustered across the North Atlantic and equatorial Pacific, as well as marginal
 840 basins including the South China and Arabian Seas (Fig. 3a,b). $U^{K'_{37}}$ records dominate in the Northern Hemisphere, where
 TEX₈₆ records show a more global distribution, even reaching the far reaches of the Southern Hemisphere ($> 60^{\circ}\text{S}$). Both
 planktic and benthic Mg/Ca records are most abundant in the tropical to subtropical and Southern Hemisphere polar region.
 The GF records are comparatively sparse, restricted to specific regions like East African Margin and western Indian Ocean
 (Fig. 3). Similarly Δ_{47} records are limited in their geographical distribution, with coccolith-derived records (e.g., UOT)
 845 primarily from the Atlantic and Southern Oceans, and benthic foraminifera-derived records (e.g., BWT) from the Indian Ocean
 and Tasmanian region.

Temporally, peak data density occurs between 5.0 and 7.0 Ma and between 13.0 and 15.0 Ma, with $U^{K'_{37}}$ records being the
 most abundant type in the latest Miocene, whereas Mg/Ca records are the most abundant type in the Middle Miocene (Fig. 3c;
 Fig. 4). This higher representation of the latest Miocene is most likely due to the higher abundance of preserved sediments
 850 from this time interval, better preservation of organic biomarkers in comparison to the Early and Middle Miocene, and lower
 global temperatures allowing application of the $U^{K'_{37}}$ -based temperature proxy to a range below 29°C . The abundance of
 Middle Miocene temperature data reflects efforts to capture major climate transitions, such as the MCO and the MMCT. Δ_{47}
 data are largely concentrated between 10 and 17 Ma. GF data cover the Middle Miocene to Late Miocene, although there are
 limited records due to the specific extremely good preservation necessary for a robust interpretation of temperature using this
 855 proxy. In contrast, TEX₈₆ records broadly cover the entire Miocene, including the data-sparse Early Miocene.

Although most proxy records capture myr-scale climate change across the Miocene, some records with kyr-scale resolution
 provide snapshots of orbital variability: for $U^{K'_{37}}$, orbital-resolution records are available at Sites 846 (Lawrence et al. 2020;
 Herbert et al. 2016), 884 (Herbert et al. 2016; Nirenberg and Herbert, 2025), U1318 (Sangiorgi et al. 2021), U1387 (Tzanova
 and Herbert 2015), QZ6 (Wang et al. 2021), and several Mediterranean sections (Herbert et al. 2016; Tzanova et al. 2015). For
 860 TEX₈₆, high-resolution records exist at Sites 846 (Lawrence et al. 2020), 959 (van der Weijst et al. 2022; Wubben et al. 2024),
 U1318 (Sangiorgi et al. 2021), QZ6 (Wang et al. 2021), and Mediterranean sites (Besiou et al. 2024; Sabino et al. 2020;
 Kontakiotis et al. 2022). For Mg/Ca, orbital-scale resolution is available at Sites 1146 (Holbourn et al. 2010, 2018), U1443
 (Martinot et al., 2022), U1448 (Jöhnck et al. 2020), 929 (Mawbey and Lear 2013), and 1171 (Shevenell et al. 2004, 2008).
 These span precession-scale resolution ($\sim 3\text{--}10$ kyr: Sites 846, 884, 959, 1146, U1443, U1448, QZ6) to obliquity-scale
 865 resolution ($\sim 11\text{--}20$ kyr: Sites 907, 982, U1318, U1387, 1171). No Δ_{47} or glassy foraminifera records currently reach orbital
 resolution.

Overall, data from different proxies in the Miocene are distributed unevenly (Fig. 4). TEX₈₆ and $U^{K'_{37}}$ provide broad latitudinal
 coverage and temporal continuity, especially in the latest Miocene, whereas Mg/Ca, Δ_{47} , and GF exhibit more limited spatio-
 temporal coverage, with data clustered in the tropics and Middle to Late Miocene. This constrained spatial and temporal
 870 distribution reflects the challenges of using foraminifera-based temperature reconstructions, which are dependent on the
 availability of well-preserved specimens, e.g. glassy foraminifera for GF-derived temperature reconstruction. In addition,
 although analytical constraints on sample size have improved, foraminifera-based Δ_{47} is also limited by the large number of
 tests needed for analysis.

Looking to the future, the MioOcean data compilation underscores the need for targeted sampling in underrepresented regions
 875 (e.g., the Southern Ocean, Indian Ocean, South Pacific, and high northern latitudes) and time intervals (e.g., the early Miocene,
 $\sim 19\text{--}23$ Ma) to better constrain the spatial and temporal trends of Miocene ocean temperatures. Furthermore, improved
 temporal resolution that captures glacial-interglacial variability over critical intervals of climate change, now possible thanks
 to astrochronology, is needed to better understand underlying driving processes.



880 **Figure 3. (a) Spatial distribution of sampling sites by proxy type, with the size of each point scaled to the number of entries at each**
 885 **site. (b) Latitudinal distribution of entries binned in 10-degrees intervals. (c) Temporal distribution of entries binned in 1-Myr**
intervals. Colors and shading indicate proxy type.

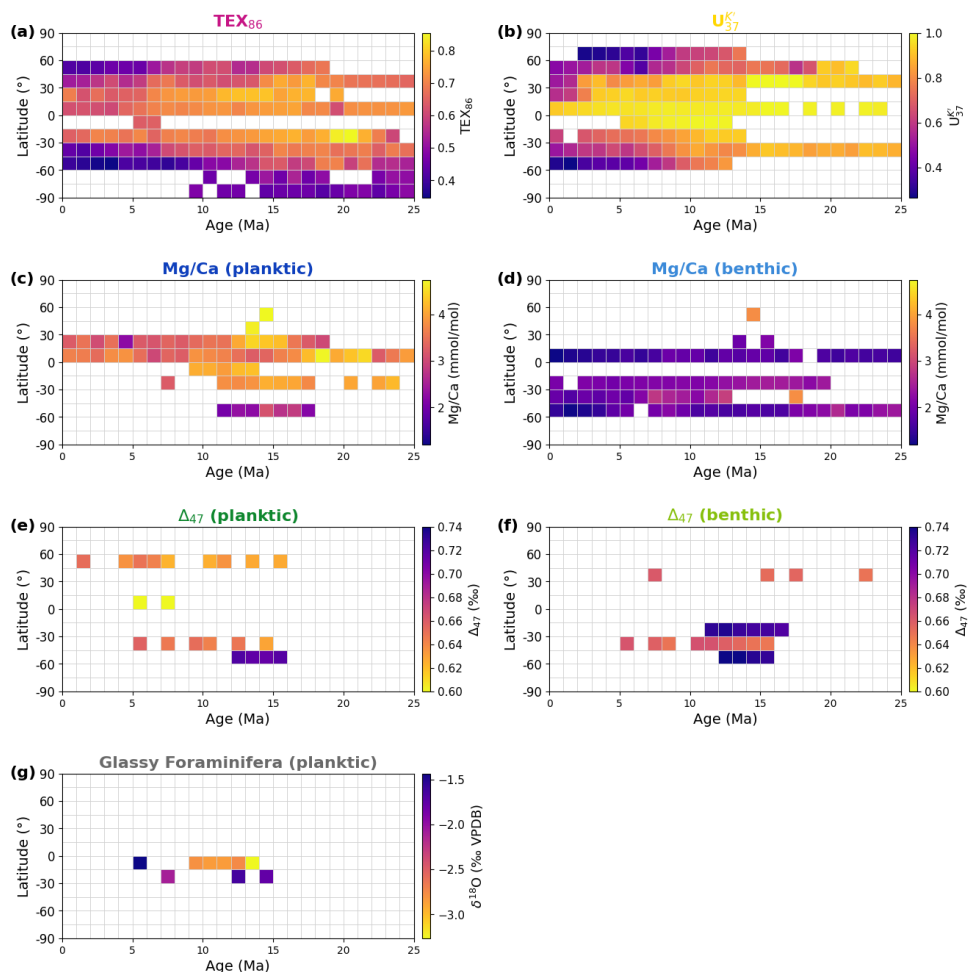


Figure 4. Spatio-temporal distribution of proxy data for MioOcean dataset, displaying heat maps of proxy values for TEX_{86} , U^{K}_{37} , Mg/Ca , Δ_{47} , and glassy planktic foraminifera proxies over the last 25 Ma. Data are averaged in 1-million-year intervals and organised by 15° latitude bands. Warmer colours (yellow) indicate warmer temperatures within each temporal and latitudinal bin. Because Δ_{47} and $\delta^{18}\text{O}$ are inversely related to temperature, their colour scales are reversed relative to the other proxies so that yellow consistently denotes warmer conditions throughout the figure.

3.2 Multi-proxy potential

A central question in paleoclimate reconstructions is whether different temperature proxies converge toward a consistent signal or whether certain proxies are more reliable under specific conditions. The MioOcean dataset integrates five temperature proxies, each with unique strengths and limitations. By compiling key records into a common MioOcean age framework and calibrating proxies consistently between sites, the MioOcean database presents a unique opportunity to investigate inconsistencies in temperatures reported by different proxies. Comparing multi-proxy records across individual sites, at nearby locations, and across varying temporal resolutions offers useful information on their consistency and suitability (Fig. 5).

The degree of agreement between proxies varies depending on the site and resolution of available data. Sites with multiple proxies but poor temporal overlap (e.g., Site 926, Fig. 5b) show significant discrepancies, making it difficult to directly compare proxy signals. At sites where proxies overlap in terms of timing and resolution but diverge in temperature (e.g., Site 1085, Fig. 5c, Rommerskirchen et al. 2011), these differences may be used to try to understand the underlying mechanism (e.g., habitat depth differences, seasonality biases, or regional oceanographic variability). The best-case scenario to compare



multi-proxy records are sites where proxies have good temporal overlap and similar resolution (e.g., Sites 982 and 1171, Fig. 5 (d, e); Super et al. 2020; Herbert et al. 2016; Mejía et al. 2025; Leutert et al. 2020; Shevenell et al. 2004, 2008), which exhibit a more coherent temperature trend, with minor variations likely attributable to differential proxy sensitivities or calibration differences. With future work in mind, the multiproxy comparisons enabled by this work could also be employed towards enabling objective calibration selection, at least for specific regions or periods of time. As seen in previous sections, three of the five proxies in the database could not justifiably be assigned a single calibration equation (Δ_{47} , TEX_{86} , planktic Mg/Ca).

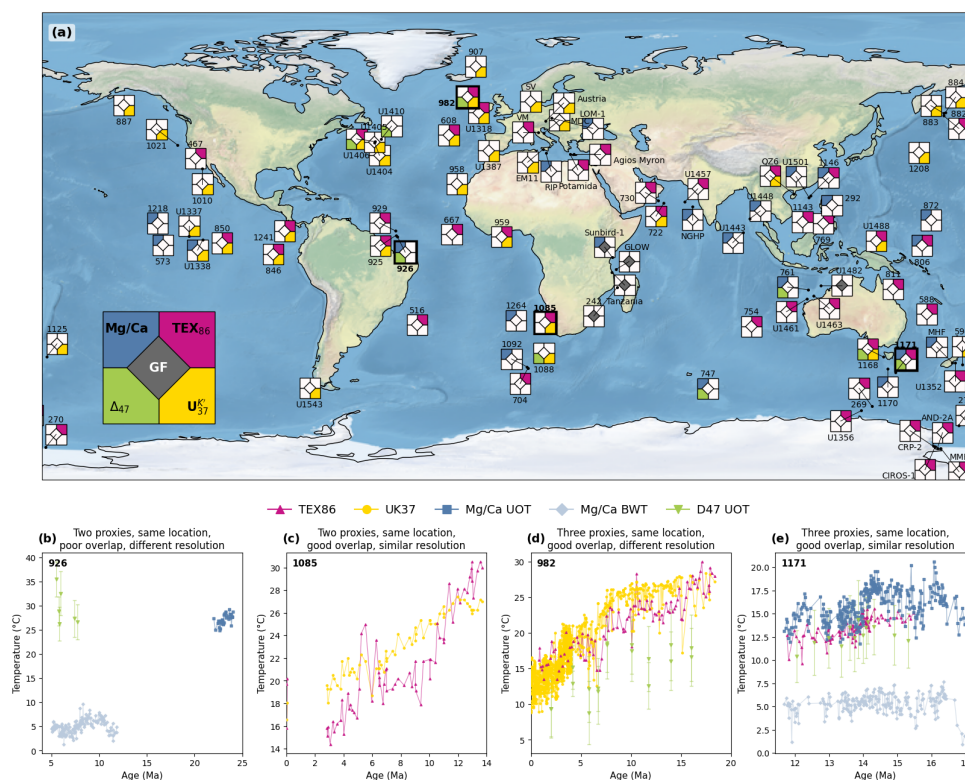


Figure 5. (a) Global distribution of MioOcean sites with available temperature proxy data. Each site is represented by a pie chart indicating the presence of different proxies: TEX_{86} (pink), U^{K}_{37} (yellow), Mg/Ca (blue), Δ_{47} (green), and glassy foraminifera (gray). Examples of multi-proxy temperature comparisons at individual sites. Error bars on Δ_{47} data points show published temperature uncertainties. (b) Published temperatures for Site 926 (western equatorial Atlantic, Ceará Rise) showing poor temporal overlap between Δ_{47} UOT (Tanner et al., 2025) and Mg/Ca UOT (Greenop et al., 2019; Lear et al., 2003) and different temporal resolutions. (c) Site 1085 (southeast Atlantic) showing good agreement between TEX_{86} and U^{K}_{37} with similar resolution (Rommerskirchen et al., 2011). (d) Site 982 (North Atlantic) with three co-located proxies: TEX_{86} and U^{K}_{37} (Super et al., 2020; Herbert et al., 2016) and Δ_{47} (two different coccolithophore size fractions, Mejía et al., 2025). (e) Site 1171 (Southern Ocean) with three co-located proxies: TEX_{86} (Leutert et al., 2020) using the Ho and Laepple (2016) subsurface calibration, Mg/Ca (Shevenell et al., 2004; 2008), and Δ_{47} (Leutert et al., 2020). Site abbreviations: VM, Vicchio Formation; MDC, Mediterranean site MED_mdc; EM11, Mediterranean site MED_em11; RIP, Ras-il-Pellegrin; GLOW, GLOW 4-BX; SV, Søndre Vium; NGHP, NGHP-01-01 (National Gas Hydrate Programme); AND-2A, ANDRILL site 2A; CIROS-1, Cenozoic Investigations in the Ross Sea site 1; CRP-2, Cape Roberts Project site 2; MME, McMurdo Erratics; MHF, Mount Harris Formation; QZ6, Qiongzong 6.

4 Data and code availability

The MioOcean data compilation is publicly accessible through the MioOcean website (<https://mioocean.com>) or through Zenodo (doi: 10.5281/zenodo.22258386; Sosdian et al., 2026). The record is currently restricted; editors and reviewers have access via a private link provided to the journal. Upon acceptance, the record will be made public under the same DOI. All Python code used for the MioOcean temperature compilation, including calculation of proxy temperatures, paleolatitude and



paleolongitude estimates, and merging of proxy and age model file, is publicly available on GitHub at https://github.com/audersea/mio_compilation. The code for the MioOcean Streamlit dashboard is available at https://github.com/audersea/mio_ocean. Both repositories are maintained under version control and will accommodate future updates to the database. All references used, at the time of publication, as data sources for the MioOcean data compilation are listed in Supplementary File S4.

5 Conclusions and future outlook

Organic and inorganic proxies provide kyr to Myr resolution ocean temperature records from across the global ocean, and are essential for understanding Miocene climate change and climate-carbon cycle relationships, enabling contextualization of modern anthropogenic climate trends. The MioOcean international community effort was formed to build upon the momentum in the Miocene proxy and age model community and use multidisciplinary expertise to re-evaluate proxy-derived ocean temperatures in line with updated proxy systematics, underpinned with revisited age models.

Our first output is the MioOcean database, including data from 94 sites, 101 publications, and nearly 22,941 paleotemperatures, supported by the verification, standardisation and revision of age models for 38 key sites. This effort has been four years in the making, with 50 researchers from 13 countries across four continents and across career stages collaborating together in online and in-person forums. The MioOcean Streamlit online data visualization platform presented here alongside the database is designed for users with a range of experience levels and diverse disciplines, enabling both simple and advanced interrogation of proxy and age model datasets. In addition to standardizing data contained in the database, our approach to FAIR (Findable, Accessible, Interoperable, and Reusable) compliant data compilation open-access resources strengthens the quality and reproducibility of paleoclimate research and provides a model for large-scale paleoclimate databases.

The MioOcean database is comprehensive, including five marine temperature proxies and revised age model information. It was compiled using a modern data curation and management structure, with the aim that it can be used and updated by the Miocene paleoceanography and paleoclimatology community for the next decades. Records in the database resolve orbital to long-term trends in ocean temperature at a regional and global scale. Interpretation of these records can provide insight into fundamental questions in Miocene climate. For instance, evaluating the coherence of long-term zonal and meridional UOT and BWT gradients alongside ice volume estimates will help decipher the role of cryosphere development (e.g., MMCT) and the nature of the ice volume-to-temperature relationship (e.g., decoupling during Late Miocene). Moreover, assessing the drivers of orbital-scale temperature variability will aid in determining the Earth system response to astronomical forcing. Further, teasing apart temperature trends in key regions (e.g., Eastern Equatorial Pacific, the circum-Antarctic latitudes, North Pacific, North Atlantic, West Pacific Warm Pool) will help disentangle regional and global drivers of ocean temperature in the Miocene.

In addition to interpreting temperature trends, rhythms, and aberrations, compilation of archives from multiple proxies provides a comprehensive testbed to explore proxy systematics and assumptions and identify gaps in spatiotemporal data coverage. For example, many proxy archives record UOT, but precise determination of signal carrier water depth habitat is difficult. Review of multi-proxy records from a range of ocean basins and Miocene time intervals can aid in determining calcification depth for inorganic proxies and depth of production of organic compounds. Cross-comparison of temperature trends will enable discussion of pros and cons of parameter and calibration selections in converting proxy values to temperatures. Further, although there are good examples of orbitally resolved temperature records (e.g., ODP sites 1146 and 1171), these are limited across the Miocene and global oceans; spatial coverage of data availability varies, depending on proxy and region. Highlighting gaps in spatial and temporal coverage provides a platform to focus future efforts (e.g., using scientific ocean drilling archives). Moving forward, integrating additional proxies and archives (e.g., benthic $\delta^{18}\text{O}$, ostracods, and diatoms) with MioOcean



records will help address challenges in reconstructing ocean temperatures from these archives, including the limited applicability of modern transfer functions to the Miocene due to the presence of many extinct planktic foraminifera taxa. Building on this effort, MioOcean has coordinated two additional working groups that will (1) use this database to assess global mean surface and land temperature and Earth's climate sensitivity during the Miocene and (2) cross-validate multi-proxy approaches to reconstructing ocean temperature, as well as investigating orbital cycles and long-term climate trends over the epoch. With a view to the future, lessons learned from the MioOcean effort and database are twofold. First, the database and its exploration will provide critical insights on warmer-than-modern climate and climate-carbon dynamics, critical for the climate modelling community and ongoing MioMIP efforts, as well as enhancing the ability to further refine temperature calibration selections for some proxies. Second, insights from the management and structure of the MioOcean effort, ensuring inclusivity and diversity are at its foundation, will foster future efforts such as this and continued innovation to tackle future climate challenges.

6 Author contribution

Contributions follow the CRediT taxonomy (<https://credit.niso.org>) and are organized in three tiers by project role: Steering Committee (Tier 1), Working Group Leads (Tier 2), and Working Group Members (Tier 3). To avoid repetition, contributions shared across a tier are stated once in the tier preamble; each individual entry then lists working-group-specific contributions (labelled by working group) and any additional project-level (MioOcean) roles.

Tier 1 — Steering Committee. A.A., A.H., S.M. and S.S. jointly directed the MioOcean project and each contributed to project-level Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, and Writing – review & editing. Additional and working-group-specific contributions: **A.A.** — project-level Resources and Code development; MioTEX (Lead): all roles except Funding acquisition and Resources; MioData: Data curation, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing; MioMg/Ca: Code development, Validation, Visualization, Writing – review & editing. **A.H.** — MioMg/Ca: Writing – review & editing. **S.M.** — MioAge: Formal analysis, Investigation, Methodology, Writing – review & editing; MioMg/Ca: Writing – review & editing; MioD47 (Lead): all roles except Resources and Code development. **S.S.** — project-level Resources; MioMg/Ca (Lead): Conceptualization, Data curation, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Tier 2 — Working Group Leads. **A.J.D.** — MioAge (Lead): all CRediT roles; MioData: Data curation, Investigation, Writing – review & editing; MioMg/Ca: Conceptualization, Data curation, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing; MioOcean: Visualization, Writing – original draft, Writing – review & editing. **A.V.H.** — MioMg/Ca (Lead): Conceptualization, Data curation, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – review & editing. **D.L.** — MioAge (Lead): all roles except Funding acquisition, Resources, and Code development. **D.T.** — MioAge (Lead): all roles except Code development; MioOcean: Visualization, Writing – original draft, Writing – review & editing. **F.B.G.** — MioGF (Lead): Conceptualization, Data curation, Investigation, Project administration, Supervision, Writing – original draft, Writing – review & editing; MioOcean: Writing – original draft, Writing – review & editing. **J.N.** — MioUK37 (Lead): Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing; MioOcean: Writing – original draft, Writing – review & editing. **K.K.** — MioMg/Ca (Lead): Conceptualization, Data curation, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing; MioAge: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing; MioOcean: Writing – original draft, Writing – review & editing. **N.S.** — MioData (Lead): all roles except Funding acquisition, Resources, and Writing – original draft; MioAge (Database Lead): Code



development, Validation. **X.L.** — MioTEX (Lead): all roles except Funding acquisition and Resources; MioUK37: Conceptualization, Formal analysis.

Tier 3 — Working Group Members. **A.Cl.** — MioD47: Conceptualization, Data curation, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing. **A.Cr.** — MioAge: Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **A.Sh.** — MioTEX: Data curation, Methodology, Validation, Writing – original draft, Writing-review & editing. **A.Sl.** — MioTEX: Data curation, Methodology, Validation, Writing – original draft, Writing – review & editing; MioOcean: Writing – original draft. **B.W.** — MioAge: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **C.B.** — MioMg/Ca: Conceptualization, Data curation, Investigation, Methodology, Validation, Visualization, Writing – review & editing; MioOcean: Writing – review & editing. **C.H.L.** — MioMg/Ca: Conceptualization, Data curation, Investigation, Methodology, Validation, Visualization, Writing – review & editing. **D.E.** — MioGF: Formal analysis, Methodology, Code development, Writing – original draft, Writing – review & editing; MioOcean: Writing – original draft, Writing – review & editing. **D.K.** — MioAge: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **D.O.** — MioAge: Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **E.J.** — MioMg/Ca: Conceptualization, Data curation, Investigation, Methodology, Code development, Validation, Visualization, Writing – original draft, Writing – review & editing. **E.M.** — MioUK37: Conceptualization, Data curation, Investigation. **E.S.** — MioAge: Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **E.W.** — MioTEX: Data curation, Methodology, Validation, Writing – review & editing. **F.S.** — MioTEX: Data curation, Methodology, Validation, Writing – review & editing. **G.A.** — MioAge: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **H.S.** — MioD47: Conceptualization, Data curation, Methodology, Project administration, Writing – review & editing. **J.K.** — MioAge: Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **K.L.** — MioUK37: Conceptualization, Data curation, Investigation. **K.M.M.** — MioData: Data curation. **K.N.K.** — MioD47: Conceptualization, Data curation, Methodology, Project administration, Writing – review & editing. **K.S.** — MioTEX: Data curation, Methodology, Validation, Writing – review & editing. **M.B.** — MioUK37: Conceptualization, Data curation, Investigation. **M.R.** — MioAge: Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **M.Z.** — MioD47: Conceptualization, Data curation, Methodology, Project administration, Supervision, Writing – review & editing. **N.M.** — MioD47: Conceptualization, Data curation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. **P.M.** — MioMg/Ca: Conceptualization, Data curation, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **S.F.** — MioTEX: Data curation, Methodology, Validation, Writing – review & editing. **T.H.** — MioUK37: Conceptualization, Data curation, Investigation. **T.S.** — MioD47: Conceptualization, Data curation, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing. **T.W.** — MioAge: all roles except Project administration, Supervision, and Visualization. **T.v.P.** — MioAge: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **V.T.** — MioD47: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **W.Kr.** — MioAge: Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **W.Ku.** — MioAge: Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing; MioMg/Ca: Conceptualization, Data curation, Investigation, Methodology, Validation, Visualization, Writing – review & editing. **W.S.** — MioUK37: Data curation, Investigation. **Y.Z.** — MioTEX: Data curation, Methodology, Validation, Writing – review & editing.



7 Competing interests

1055 The authors declare that they have no conflict of interest.

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 1070 authors have applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript (AAM) version arising from this submission.

9 Appendix A: Detail of Δ_{47} -based temperature uncertainty calculation

In contrast to other paleothermometers, the uncertainty associated with Δ_{47} -derived temperatures is dominated by analytical error, with a comparatively small contribution from calibration uncertainty. In accordance with community best practice, our
 1075 Δ_{47} -based temperature uncertainties are calculated by propagating together analytical and calibration errors, and reporting at 68 and 95 % confidence intervals (Fernandez et al., 2017).
 To maintain consistency with the error propagation methods used with the respective calibrations, the method selected to propagate the calibration uncertainty is dependent on the calibration used. Thus, uncertainty on temperatures calculated using the archive-specific Meinicke et al. (2021) and Clark et al. (2025) calibrations is calculated differently to the method used for
 1080 temperatures calculated with the Daëron and Vermeesch (2024) calibration. The respective methods, however, do not introduce significant differences in the numerical value of fully propagated uncertainty (i.e., the numerical value of uncertainty is nearly identical across the selected calibrations), as the methods are analogous over the temperature ranges of interest.
 To reproduce MioOcean Δ_{47} temperatures, the mean Δ_{47} value listed in the database is fed into the rearranged calibration equation of choice. To propagate analytical and calibration error into the temperature uncertainty using either the Meinicke et
 1085 al. (2021) or Clark et al. (2025) calibrations, we use the Monte Carlo (MC) method, consistent with Meinicke et al. (2021). To reproduce this calculation, two types of information are required: the standard error of the mean Δ_{47} value, calculated from the replicates included in the respective temperature bin; and probability distributions of both the calibration slope and intercept, which are required for random draws in the MC simulations. Bootstrapping, with resampling, was used by Meinicke et al. (2021) to generate these distributions for their planktic foraminifer calibration dataset. We reproduced those author's methods,
 1090 using 100,000 repetitions, the 'Isoplot R' (Vermeesch, 2018) and 'boot' packages in R, but with the Clark et al. (2025) coccolith calibration dataset (using all data included in their equation 2), to generate equivalent distributions to enable application of the MC method for propagating uncertainty for temperatures calculated using the Clark et al. (2025) calibration. Again following



the choices applied in Meinicke et al. (2021) for consistency, we ran 5000 MC simulations using these distributions for any temperatures calculated with the Clark et al. (2025) calibration, while using the existing, equivalent distributions generated by
 1095 Meinicke et al. (2021) for temperatures calculated with that calibration equation. Histograms of these distributions are shown
 Fig. A1. Though these distributions are relatively straightforward to reproduce, exact values will vary slightly with each run
 of the bootstrapping experiment, and thus for reproducibility and convenience, we enclose them herein as supplemental files
 (Meinicke et al. (2021) foraminifera related slopes and intercepts in Table S1; Clark et al. (2025) coccolithophore data related
 slopes and intercepts in Table S2).

1100

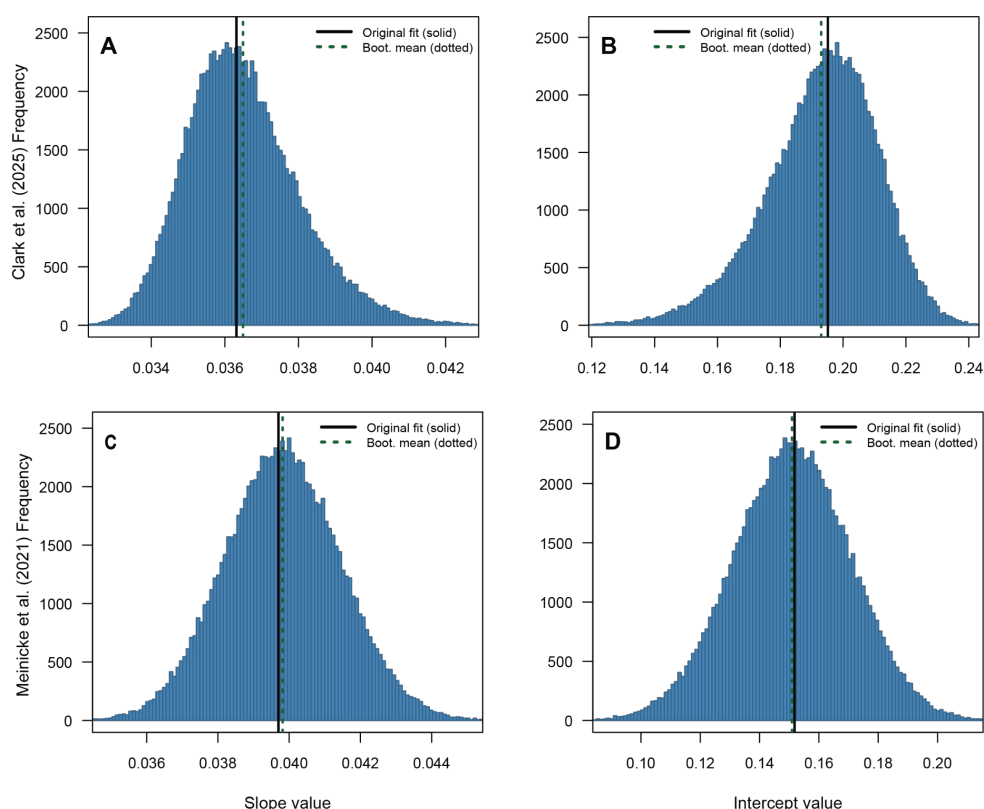


Fig. A1. Histograms of the (a, c) slopes and (b, d) intercepts generated by applying a bootstrapping experiment (with resampling, 100,000 repetitions) to the (a, b) coccolith calibration data used in equation 2 of Clark et al. (2025) or (c, d) foraminifera data from Meinicke et al. 2021. The slight distribution skew in (a, b) is due to uneven temperature coverage, particularly at the colder end. This spacing is a reality of calibration data availability, resulting from the time and resource intensive requirements for culturing or sediment trap sampling of living organisms. The corresponding tabulated slope and intercept data can be found in supplemental table S1 (foraminifer data, Meinicke et al. 2021) and Supplemental Table S2 (coccolithophore data, Clark et al. 2025).

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For full transparency, it is important to note some minor differences in the calibration equation published in Clark et al. (2025) and the equation used by MioOcean. For consistency and ease of implementation of uncertainty propagation, we used the York regression implemented in the Isoplot R package to recalculate the coccolithophore temperature calibration equation. Regardless of using identical data, there is a slight difference to the third significant digit calculated using the methods
 1115 employed here, compared to the method used in Clark et al. (2025) (Williamson-York excel spreadsheet tool; Cantrell, 2008). We obtained, and implemented, for MioOcean:



$$\Delta_{47} = 0.0365 \frac{10^6}{T^2} + 0.193 \quad (A1)$$

1120 Compare to equation (2) published in Clark et al. (2025):

$$\Delta_{47} = 0.0366 \frac{10^6}{T^2} + 0.191 \quad (A2)$$

1125 These differences have a negligible impact on the calculated temperature; over the range of observed ocean temperatures (i.e., 0 to 40 °C) differences are 0.2 to 0.4 degrees. These differences are well within one standard error, and thus insignificant to any paleoclimatic or paleoceanographic interpretation.

For Δ_{47} temperatures calculated using the Daëron and Vermeesch (2024) calibration, we used the D47calib script (<https://github.com/mdaeron/D47calib>), which contains all calibration data required for error propagation. This script was developed for and published with the Daëron and Vermeesch (2024) calibration, employs an ‘omnivariant general least-squares’ regression, and propagates analytical and calibration uncertainty using Jacobian matrix algebra. As stated earlier, for 1130 the temperature ranges of interest, the MC method described above and the Jacobian matrix algebra approach are analogous, as demonstrated by the near identical temperature uncertainties produced by either approach.

10 Appendix B: Revised Age Information Summary

1135 This appendix consists of Table B1, comprising a summary of the sites for which age models have been revised and new information is available in the MioOcean database. Critical details such as which proxy records are available at each site and the age range for the revised age model are listed. Brackets around Revised = an interval was revised, not entire age range of available data. Define R/V/S

Table B1: Overview of updated age models for 38 key sites with updated age models, age ranges and other critical parameters. Age model categories indicate the type of information underpinning it, and include biostratigraphy (B), magnetostratigraphy (M), astrochronology (A), and finally, chemostratigraphy and/or radiometric dating (+). Two ‘sets’ of codes (separated by a semicolon) indicates one or more segments of the stratigraphy are pinned to different types age information. Status indicates whether existing age models were verified and standardised, or whether revision was also required; brackets indicate that only a section of the available age model(s) were revised. See section 2.3.3 for an explanation of these terms.

Site	Proxy availability	MioOcean age model status (published age used where no MioOcean age exists)	MioOcean Age Model category:	Absolute Age Change Mode (Myr)	Absolute Age Change Largest (Myr)	MioOcean Implemented/ applied Age Model range (Ma) (out-of-range samples use published age)
516	TEX ₈₆	Revised, Verified and Standardised	BM+	0	2.852	1.205-67.765 Ma
588	TEX ₈₆	Revised, Verified and Standardised	BM+	0	2.406	0-23.28 Ma
594	U ^K ₃₇	Revised, Verified and Standardised	BM+	0.069	0.806	0-13.646 Ma
608	TEX ₈₆ , U ^K ₃₇	Revised, Verified and Standardised	BM	0	1.708	0-27.978 Ma
667	TEX ₈₆	Revised, Verified and Standardised	BM	0.006	1.023	0-33.502 Ma



704	TEX ₈₆	Revised, Verified and Standardised	BM	0	2.733	0-29.872 Ma
722	TEX ₈₆ , U ^{K'} ₃₇	Revised, Verified and Standardised	BM; B	0.007	1.016	4.95-15.781 Ma
730	TEX ₈₆	Revised, Verified and Standardised	B	0.38	7.121	0-15.727 Ma
747	Mg/Ca, Δ ₄₇	Revised, Verified and Standardised	BM+	0.002	3.252	0-24.409 Ma
754	TEX ₈₆	Revised, Verified and Standardised	B	0.006	0.022	0-28.349 Ma
761	Mg/Ca, Δ ₄₇	Verified and Standardised	A	0.027	0.448	9.879-18.43 Ma
806	Mg/Ca, TEX ₈₆	Revised, Verified and Standardised	B	0.049	1.128	0-22.611 Ma
846	TEX ₈₆ , U ^{K'} ₃₇	Revised, Verified and Standardised	A; B	0.265	0.271	0-16.894 Ma
850	TEX ₈₆ , U ^{K'} ₃₇	(Revised,) Verified and Standardised	A; B	0.001	0.392	0-11.762 Ma
872	Mg/Ca	Revised, Verified and Standardised	B	1.065	1.067	3.988-23.378 Ma
883	U ^{K'} ₃₇	Revised, Verified and Standardised	BM	0.013	0.932	0-17.497 Ma
884	U ^{K'} ₃₇	Revised, Verified and Standardised	M	0.007	0.33	0-22.036 Ma
925	Mg/Ca, TEX ₈₆ , U ^{K'} ₃₇	(Revised,) Verified and Standardised	A; B	0	1.198	0-40.817 Ma
926	Mg/Ca, Δ ₄₇	(Revised,) Verified and Standardised	A; B	0	2.263	0-21.457 Ma
982	TEX ₈₆ , U ^{K'} ₃₇ , Δ ₄₇	(Revised,) Verified and Standardised	A; B	0.114	1.612	4.258-20.216 Ma
1085	TEX ₈₆ , U ^{K'} ₃₇	Verified and Standardised	B	0.035	1.11	1.694-14.091 Ma
1088	Mg/Ca, Δ ₄₇ , U ^{K'} ₃₇	(Revised,) Verified and Standardised	A; B	0.967	0.967	2.989-17.261 Ma
1092	Mg/Ca	Revised, Verified and Standardised	A+	0.007	0.064	12.402-14.775 Ma
1143	TEX ₈₆	Revised, Verified and Standardised	B	0.01	0.827	0-12.638 Ma
1146	Mg/Ca, TEX ₈₆	(Revised,) Verified and Standardised	A	0	2.476	4.81-21.593 Ma
1170	Mg/Ca	Revised, Verified and Standardised	M	0.022	0.212	12.696-21.055 Ma
1171	Mg/Ca, TEX ₈₆ , Δ ₄₇	Revised, Verified and Standardised	M+	0	0.34	10.915-16.805 Ma
1241	TEX ₈₆ , U ^{K'} ₃₇	(Revised,) Verified and Standardised	A; B	0.109	0.589	4.859-11.985 Ma
1264	Mg/Ca	Verified and Standardised	A	0.004	0.029	0-31.337 Ma
U1318	TEX ₈₆ , U ^{K'} ₃₇	Verified and Standardised	M	0.036	1.165	12.614-16.638 Ma
U1337	U ^{K'} ₃₇ , Mg/Ca	(Revised,) Verified and Standardised	A	0.006	0.091	0-19.042 Ma
U1338	Mg/Ca, U ^{K'} ₃₇	Verified and Standardised	A	0	0.476	2.996-16.22 Ma
U1356	TEX ₈₆	Revised, Verified and Standardised	BM	0.001	2.125	0-54.468 Ma
U1406	TEX ₈₆ , Δ ₄₇ , U ^{K'} ₃₇	(Revised,) Verified and Standardised	A	1.583	1.988	16.752-29.527 Ma
U1443	Mg/Ca	Verified and Standardised	A	0	0.003	4.43-10.34 Ma
U1457	TEX ₈₆	Verified and Standardised	BM	N/A	0.785	5.541-10.428 Ma
U1501	Mg/Ca	Revised, Verified and Standardised	B+	0.613	2.183	0-34.61 Ma
AND-2A	TEX ₈₆	Revised, Verified and Standardised	BM+	0.004	0.14	11.091-20.221 Ma



11 Supplemental file list

Supplementary Tables [S1](#) and [S2](#): Slopes and intercepts generated via bootstrapping (with resampling, 100,000 iterations), used for random draws in the Monte Carlo simulations employed to estimate Δ_{47} temperature calibration uncertainty. Table S1 includes slopes and intercepts for the Meinicke et al. (2021) calibration. Table S2 includes slopes and intercepts for the Clark et al. (2025) calibration.

Supplementary Table [S3](#): Overview of all sites included in the MioOcean database at the time of publication, including key information per site (proxy type(s), resolution range, latitude, longitude, water depth, ocean basin/region, and original reference(s). Resolution refers to resolution on originally published timescale.

Supplemental File [S4](#): Bibliography, organized by proxy, of all publications used as temperature data sources now compiled within the MioOcean database.

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