



# Evaluating Late Pliocene Atlantic Meridional Overturning Circulation dynamics through biogeochemical proxy–model comparison

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**Abstract.** Atlantic Meridional Overturning Circulation (AMOC) is a major feature in the climate system, moving heat and carbon globally. Climate models suggest AMOC's strength will decrease in the coming decades, with profound implications for regional and global climate patterns. Biogeochemical proxies from benthic foraminifera tests can act as water mass tracers and provide information on deep ocean circulation during past periods of global warmth. The strength of AMOC during the Late Pliocene warm period ( $\sim 3.0\text{--}3.3$  Ma), a pseudo-analogue for future climate change, is poorly constrained, with benthic foraminiferal  $\delta^{13}\text{C}$  showing a spatially expanded North Atlantic Deep Water (NADW), whereas models often simulate a spatially retracted NADW relative to Pre-Industrial. Here we compare  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  proxies in the Atlantic for the warm mid-Piacenzian KM5c interval ( $3.205 \pm 0.02$  Ma) with four isotope-enabled climate model simulations allowing for a direct comparison between proxy data and climate models. Proxy data generally show a more expansive NADW with Antarctic Bottom Water limited to the greatest depths. Although climate models resolve key intermediate and deep water masses, differences in spatial patterns between the models are attributed to model parameterisations and boundary conditions. The models and proxy data show different deep ocean structures, which limits our ability to understand deep ocean circulation during the warm mid-Piacenzian KM5c interval and its relevance to future warming scenarios.

## 1 Introduction

The Atlantic Meridional Overturning Circulation (AMOC) is a critical component of the global climate system, acting as a major conduit for heat, salinity, nutrients, and carbon between the low and high latitudes (Talley, 2003; McCarthy et al., 2017). Comprised of a system of currents that facilitate the exchange of water between the surface and deep ocean, AMOC is driven by density gradients due to temperature and salinity (Rahmstorf, 2003; Gruber et al., 2019). AMOC transports warm, saline surface water from the tropics to the subpolar and polar North Atlantic, where it releases heat into the atmosphere, increases in density and forms North Atlantic Deep Water (NADW). NADW is a nutrient-poor water mass that returns southward at depths of  $\sim 2000\text{--}3000$  m (Heuzé, 2017). This transport of oceanic heat northwards influences regional climates in Europe and North America (Zhang et al., 2019). AMOC also plays a vital role in regulating the ocean's capacity to absorb atmospheric  $\text{CO}_2$  by ventilating the deep ocean and distributing nutrients essential for marine productivity (Katavouta et al., 2019; Whitt and Jansen, 2020). AMOC strength is predicted to decline in the near future in response to anthropogenic warming, resulting in the alteration of regional precipitation, sea level, and global heat transport (Fox-Kemper et al., 2021; Baker et al., 2025).

The mid-Piacenzian Warm Period (mPWP,  $3.3\text{--}3.0$  Ma) is often used as a modelling target to help understand future climate change because it is considered a (conditional and contextual, Burton et al., 2025) past analogue to future warmth. The mPWP is the last time in Earth's history when atmospheric  $\text{CO}_2$  levels were similar to today ( $\sim 426$  ppm, Friedlingstein et al., 2026) and the global mean sea surface temperature was estimated to be  $2\text{--}3^\circ\text{C}$  warmer than Pre-Industrial (Fig. 1; Dowsett et al., 2013; Haywood et al., 2013; McClymont et al., 2020; The Cenozoic  $\text{CO}_2$  Proxy Integration Project (CenCO2PIP) Consortium, 2023). Therefore, the mPWP is an ideal interval to evaluate AMOC behaviour during a globally warm climate state; however, previous research identified proxy data–model disagreement regarding the spatial pattern of AMOC (Ravelo and Andreasen, 2000; Zhang et al., 2021; Weiffenbach et al., 2023).

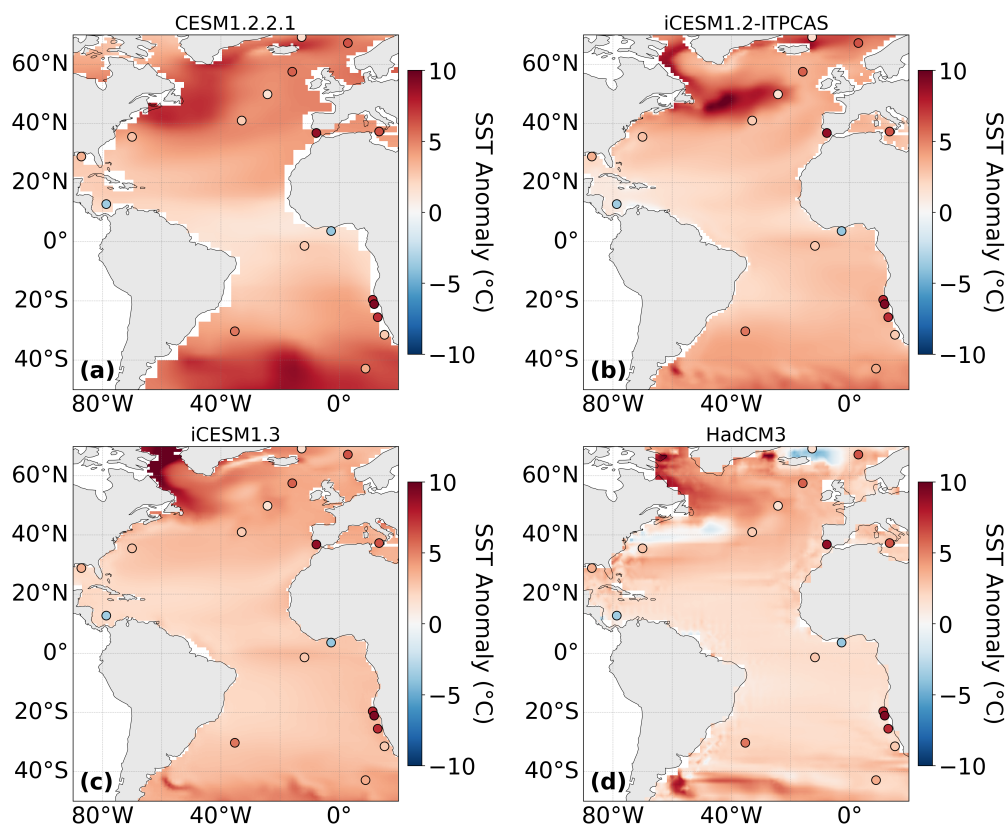


**Figure 1.** Sea surface temperature anomaly map of mid-Piacenzian KM5c with PlioVAR data (circles, McClymont et al., 2020, anomaly calculated using NOAA-ERSST5 as Pre-Industrial) with background model output from (a) CESM1.2.2.1, (b) iCESM1.2-ITPCAS, (c) iCESM1.3, (d) HadCM3.

Benthic foraminiferal carbon stable isotopes ( $\delta^{13}\text{C}$ ) and oxygen stable isotopes ( $\delta^{18}\text{O}$ ) are widely used proxies in palaeoceanography (Ravelo and Andreasen, 2000; Curry and Oppo, 2005; Ravelo and Hillaire-Marcel, 2007). In Atlantic Ocean transects (Fig. 2a), benthic foraminiferal  $\delta^{13}\text{C}$  reflects deep-water ventilation and biological productivity. NADW is a high  $\delta^{13}\text{C}$  water mass because it is well-ventilated and nutrient-depleted due to near complete nutrient utilisation in North Atlantic NADW formation areas. Benthic foraminiferal  $\delta^{18}\text{O}$  is influenced by temperature,  $\delta^{18}\text{O}$  of seawater, and species-specific isotope fractionation during calcification (Fig. 2b). The  $\delta^{18}\text{O}$  of seawater reflects global ice volume and evaporation and precipitation processes, which affect salinity. Multi-proxy approaches (including benthic foraminifera) and proxy to climate model output comparisons have aimed to find parsimonious deep circulation reconstructions (Oppo et al., 2018; Gu et al., 2020).

During the mPWP,  $\delta^{13}\text{C}$  proxy reconstructions suggest an expanded NADW relative to modern that extends into the South Atlantic, whereas climate models simulate a mid-depth confined NADW, though there is large model spread (Ravelo and Andreasen, 2000; Zhang et al., 2021; Weiffenbach et al., 2023). This data–model mismatch could be due to the nature of the comparison itself. Climate models are often not isotope-enabled so a comparison between modelling output (e.g. meridional



velocity streamfunction measured in Sv) and proxy stable isotope values are not like for like. Additionally, there is often a disparity in the time window of comparison; proxy reconstructions often average over a long time window (e.g.  $\geq 200,000$  years), whereas climate models often simulate a specific orbital configuration (i.e. Marine Isotope Stage KM5c). The mismatch could also be due to biases and uncertainties in the reconstruction of benthic foraminiferal  $\delta^{13}\text{C}$  (Mackensen et al., 1993).

50 Factors such as shifting  $\delta^{13}\text{C}$  values in the end-members of AMOC water masses, the chosen interval of comparison (e.g. broad  $\delta^{13}\text{C}$  trends vs. specific climate simulation window), and the length of the model simulation add complexity to AMOC reconstructions and data–model comparisons (Zhang et al., 2013a).

In this study, we use the benthic foraminiferal  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  records from the PlioMioVAR database and compare the proxy values to state-of-the-art isotope-enabled climate models to explore deep ocean circulation. The PlioVAR database has been

55 extensively quality- and age-model-controlled and previous studies of the PlioVAR database (the precursor to PlioMioVAR) have focused on sea surface conditions and global ice volume changes (McClymont et al., 2020, 2023). The isotope-enabled climate models are configured with the Pliocene Model Intercomparison Project Phases 1 and 2 (PlioMIP1 and PlioMIP2) boundary conditions (Haywood et al., 2011; Dowsett et al., 2016; Haywood et al., 2016; Ford et al., 2022a; Sun et al., 2024; Ren et al., 2025; Deneau et al., in review). Our study focuses on Marine Isotope Stage KM5c ( $3.205 \pm 0.02$  Ma) to evaluate the

60 spatial patterns of AMOC. Concentrating our comparison on the KM5c interval (Dowsett et al., 2016; Haywood et al., 2016), rather than a wider PRISM3D interval as in PlioMIP1 (3.264–3.025 Ma, Dowsett, 2007), filters out other sources of climate variability (e.g. orbital, Prescott et al., 2014). Additionally, using the PlioMioVAR benthic  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  and isotope-enabled model outputs allows for a more direct, pairwise data–model comparison. Here we 1) reconstruct and evaluate the AMOC structure implied by the benthic  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values, 2) describe the AMOC structure simulated by the models, and 3)

65 assess the consistency and compatibility between the proxy data and model simulations. Comparing simulated  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  distributions with proxy data enables us to assess the structure and dynamics of Pliocene deep-water masses implied by each, explore the limitations of each approach, and discuss possible improvements.

## 2 Methods

### 2.1 Proxies

70 As part of the Past Global Changes (PAGES) PlioVAR and PlioMioVAR Working Groups (McClymont et al., 2020; Ford et al., 2022b), we have curated previously published and unpublished benthic foraminiferal stable isotope data for the Pliocene that we use for AMOC spatial reconstructions (Fig. 3, Table 1). In total, 23 Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP), and International Ocean Discovery Program (IODP) sites within the Atlantic Ocean were used, of which all 23 have data for  $\delta^{18}\text{O}$  and 19 have data for  $\delta^{13}\text{C}$ . These sites are in open ocean locations and exclude sites within restricted

75 basins. We limited data to the KM5c Interglacial ( $3.205 \pm 0.02$  Ma) to ensure temporal alignment and data–model comparison fidelity following previous PlioVAR protocols (McClymont et al., 2020). Within this time range, the PlioMioVAR database provides reasonably good latitudinal and depth coverage of the Atlantic basin, although the data are somewhat concentrated

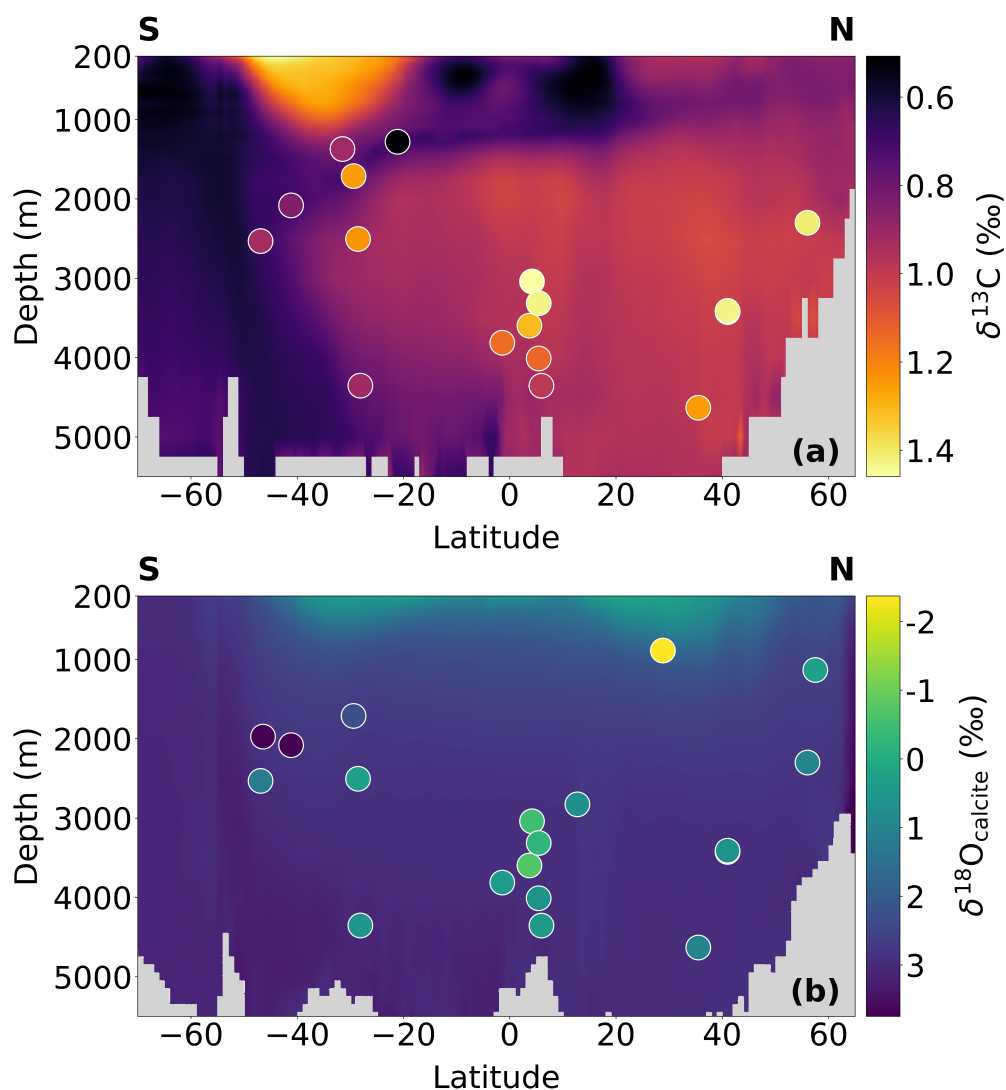


**Figure 2.** Zonal mean Atlantic transect of Holocene core top benthic foraminiferal  $\delta^{13}\text{C}$  (a) and  $\delta^{18}\text{O}$  (b) values (Schmittner et al., 2017, this study), overlain on modern-day ocean stable isotope distributions of  $\delta^{13}\text{C}$  (Eide et al., 2017) and  $\delta^{18}\text{O}$  of calcite. The  $\delta^{18}\text{O}$  of calcite was calculated from modern temperature and  $\delta^{18}\text{O}$  of seawater distributions (LeGrande and Schmidt, 2006; Reagan et al., 2023) using the relationship of Marchitto et al. (2014).

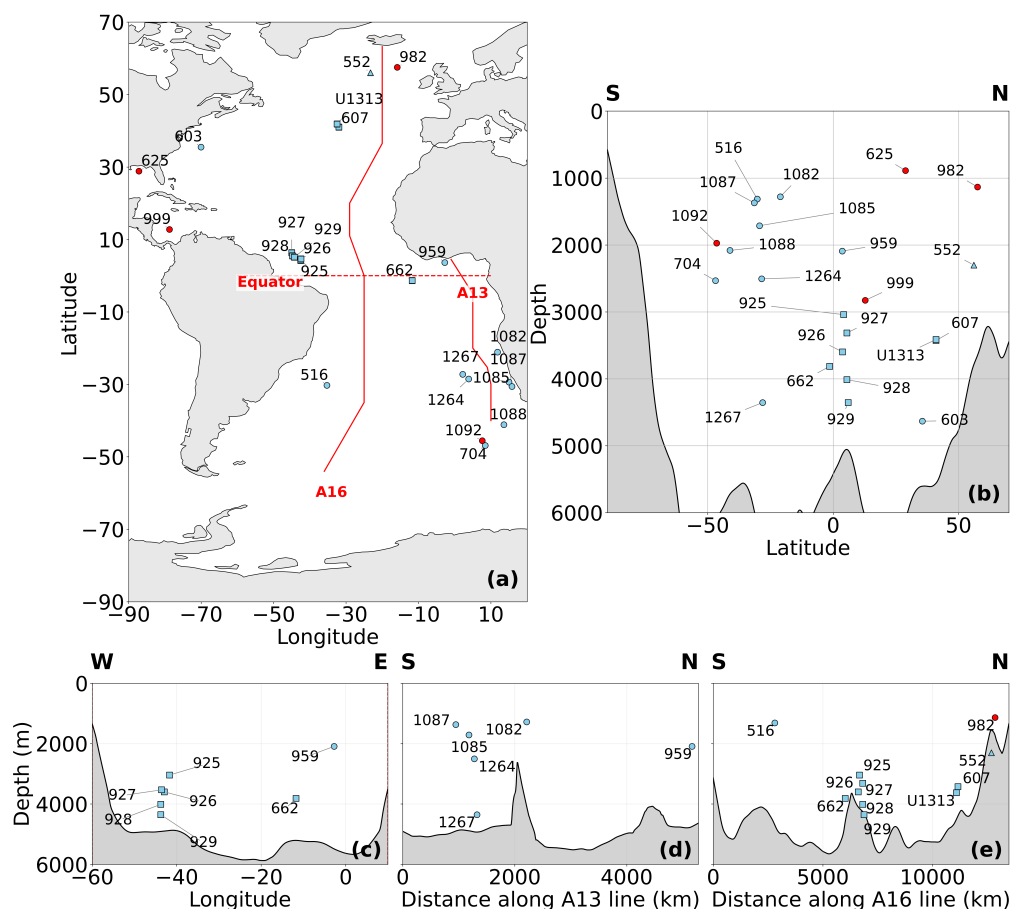


**Figure 3.** Overview of PlioMioVAR site locations, categorised by available data and foraminiferal species used in analysis. (a) Map of site locations with equatorial and eWOCE (World Ocean Circulation Experiment) A13 and A16 transects labelled, (b) zonal mean cross section from the South Atlantic to North Atlantic, (c) meridional mean across the equator, (d) south to north distance along transect line–depth cross-section along the eWOCE A13 transect and (e) south to north distance along transect line–depth cross-section along the eWOCE A16 transect. Light blue sites have available both  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values, while red sites contain only  $\delta^{18}\text{O}$  values. Square markers represent analysis from *Cibicidoides* species only, circle markers represent sites where samples were analysed from both *Cibicidoides* and *Uvigerina* species and triangle markers represent sites where samples were analysed from *Cibicidoides*, *Uvigerina*, and *Hoeglundina* species.



at latitudes between 40° S and 20° N (Fig. 3). There are some notable data gaps in the high-latitude North Atlantic (north of 45° N) and at depths  $\geq 3000$  m in the Atlantic sector of the Southern Ocean (Fig. 3).

Here, we exclusively use *Cibicidoides* spp. for the  $\delta^{13}\text{C}$  reconstruction to limit infaunal vs. epifaunal impacts on  $\delta^{13}\text{C}$  values (Fig. 3; Ravelo and Hillaire-Marcel, 2007). Owing to limited data availability, for  $\delta^{18}\text{O}$  we take a multi-species approach using available *Cibicidoides* spp., *Uvigerina* spp. and *Hoeglundina elegans* values. To account for interspecies offsets, we applied the species corrections of Marchitto et al. (2014). Specifically, +0.47‰ was added to *Uvigerina* spp. and +1.07‰ was added to *Hoeglundina elegans* to adjust to *Cibicidoides* spp. values.

We used Holocene core top data for comparisons with Pre-Industrial model runs. We used the Ocean Circulation and Carbon Cycling (OC3) data product (Schmittner et al., 2017) and/or site-specific core top data that are younger than 6 ka (Tables A1 and A2). Using the existing OC3 method, we identified Holocene core top samples within a great-circle distance ( $\delta d$ ) and vertical distance ( $\delta z$ ) from PlioMioVAR drilling sites. Where multiple samples met these criteria, we averaged the associated proxy values to obtain a single core top estimate for each site. Two sets of thresholds of  $\delta d$  and  $\delta z$  were used based on core top availability, named “conservative” ( $\delta d = 500$  km,  $\delta z = z/10$ ) and “liberal” ( $\delta d = 1000$  km,  $\delta z = z/5$ ).

## 2.2 Models

This study used output from isotope-enabled fully coupled Earth System Models (Table 2; Smith et al., 2010; Haywood et al., 2011, 2016; Brady et al., 2019; Feng et al., 2020; Ford et al., 2022a; Sun et al., 2024; Deneau et al., in review). The  $\delta^{13}\text{C}$ -biogeochemically enabled model with modified cloud albedo (CESM1.2.2.1) is set to Pre-Industrial boundary conditions with changes in cloud albedo that simulate Pliocene-like warming (Burls and Fedorov, 2014; Ford et al., 2022a). The oxygen isotope-enabled models (iCESM1.2-ITPCAS, HadCM3, and iCESM1.3) used the PlioMIP2 experimental design, which used boundary conditions from PRISM4 (Dowsett et al., 2016), which included a land-sea mask with a closed Bering Strait and Canadian Arctic Seaway, and  $\text{CO}_2$  levels set to 400 ppm. While Pre-Industrial orbital forcing is used as a boundary condition, the orbital forcing of KM5c is the same as Pre-Industrial (Haywood et al., 2016), and adjustments to bathymetry and topography accounted for the dynamic changes during the Pliocene. A closed Bering Strait has been shown to favour stronger AMOC in PlioMIP2 (Otto-Bliesner et al., 2017; Zhang et al., 2021). After model spin-up, all models were run for 2700 to 4000 model years; the re-gridded outputs plotted are the average of the last 100 model years (Table 2). The iCESM1.3 simulation was run for an additional 600 years after being branched off from an iCESM1.2 simulation that was run for 3000 years.

For the proxy data–model comparison, the  $\delta^{13}\text{C}$  output of the model was compared directly with benthic foraminiferal  $\delta^{13}\text{C}$  values. For comparison with the benthic foraminiferal  $\delta^{18}\text{O}$  values, the temperature and  $\delta^{18}\text{O}$  of seawater ( $\delta^{18}\text{O}_{\text{seawater}}$ ) of the model output were used to calculate  $\delta^{18}\text{O}_{\text{calcite}}$  using the equation from Marchitto et al. (2014) where  $t$  is the model temperature at the grid cell nearest the core depth:

$$\delta^{18}\text{O}_{\text{calcite}} - \delta^{18}\text{O}_{\text{seawater}} + 0.27 = -0.224t + 3.53 \quad (1)$$



**Table 1.** PlioMioVAR site information.

| Site       | Longitude | Latitude | Water depth (m) | References                                                           |
|------------|-----------|----------|-----------------|----------------------------------------------------------------------|
| DSDP 516   | 35.29° W  | 30.28° S | 1313            | Karas et al. (2017)                                                  |
| DSDP 552   | 23.23° W  | 56.04° N | 2301            | Shackleton and Hall (1984)                                           |
| DSDP 603   | 70.03° W  | 35.49° N | 4633            | De Schepper et al. (2013), De Schepper (2015)                        |
| DSDP 607   | 32.96° W  | 41.00° N | 3427            | Dwyer and Chandler (2009)                                            |
| ODP 625    | 87.16° W  | 28.83° N | 889             | Costanza (2007), Shakun et al. (2016)                                |
| ODP 662    | 11.74° W  | 1.39° S  | 3814            | Lisiecki and Raymo (2005)                                            |
| ODP 704    | 7.42° E   | 46.88° S | 2532            | Hodell and Venz (2013)                                               |
| ODP 925    | 43.49° W  | 4.20° N  | 3041            | Wilkens et al. (2017)                                                |
| ODP 926    | 42.91° W  | 3.72° N  | 3598            | Wilkens et al. (2017)                                                |
| ODP 927    | 44.48° W  | 5.46° N  | 3315            | Wilkens et al. (2017)                                                |
| ODP 928    | 43.75° W  | 5.46° N  | 4012            | Wilkens et al. (2017)                                                |
| ODP 929    | 43.74° W  | 5.98° N  | 4356            | Wilkens et al. (2017)                                                |
| ODP 959    | 2.74° W   | 3.63° N  | 2091            | Van Der Weijst et al. (2020)                                         |
| ODP 982    | 15.87° W  | 57.52° N | 1134            | Lisiecki and Raymo (2005)                                            |
| ODP 999    | 78.74° W  | 12.74° N | 2828            | de la Vega et al. (2020)                                             |
| ODP 1082   | 11.82° E  | 21.09° S | 1280            | Dupont et al. (2005)                                                 |
| ODP 1085   | 13.99° E  | 29.37° S | 1713            | unpublished data by Ravelo and Andreasen                             |
| ODP 1087   | 15.31° E  | 31.46° S | 1372            | Petrick et al. (2015) + unpublished data                             |
| ODP 1088   | 13.56° E  | 41.14° S | 2082            | Hodell and Venz-Curtis (2006)                                        |
| ODP 1092   | 7.08° E   | 46.41° S | 1974            | Andersson et al. (2002)                                              |
| ODP 1264   | 2.85° E   | 28.53° S | 2506            | Bell et al. (2014)                                                   |
| ODP 1267   | 1.71° E   | 28.10° S | 4355            | Bell et al. (2014)                                                   |
| IODP U1313 | 32.96° W  | 41.00° N | 3412            | Lang et al. (2014), De Schepper et al. (2013), Bolton et al. (2010b) |



**Table 2.** The isotope-enabled models used in this study. All resolution details are provided in latitude by longitude.

| Model           | Ocean resolution lat × lon                                | Mixing scheme                                   | Model run time | Configuration                                           | Publication                                                            |
|-----------------|-----------------------------------------------------------|-------------------------------------------------|----------------|---------------------------------------------------------|------------------------------------------------------------------------|
| CESM1.2.2.1     | 3° near the poles<br>increasing to 1°<br>near the Equator | Default K-profile<br>parameterisation<br>scheme | 3000 years     | Pre-Industrial<br>with cloud<br>albedo<br>modifications | Ford et al. (2022a)                                                    |
| iCESM1.3        | 1° × 1°, L60<br>depth                                     | Default K-profile<br>parameterisation<br>scheme | 3400 years     | PlioMIP2,<br>iCAM5,<br>iCLM4.0, iPOP2,<br>iCICE4        | Deneau et al. (in review)                                              |
| iCESM1.2-ITPCAS | 1° × 1°, L60                                              | Default K-profile<br>parameterisation<br>scheme | 2700 years     | PlioMIP2,<br>iCAM5.3,<br>iCLM4.0, iPOP2,<br>iCICE4      | Sun et al. (2024)                                                      |
| HadCM3          | 1.25° × 1.25°,<br>L20 depth                               | $k = 0.10 \text{ cm}^2 \text{ s}^{-1}$          | 4000 years     | PlioMIP2                                                | Valdes et al.<br>(2017); Hunter<br>et al. (2019); Ren<br>et al. (2025) |



## 2.3 Proxy data–model comparison

Our primary objective is to understand the proxy and model performance in comparison to each other. In this context we take into consideration the specific strengths and limitations of each approach (proxy- vs. model-based) in reconstructing the spatial pattern of AMOC. While the DSDP, ODP, and IODP sites provide site-specific observational evidence of past climates, they are limited in number and geographic coverage; the climate model data, by contrast, are spatially continuous but limited by grid-cell size owing to computational constraints. To evaluate the pairwise match between proxy data and model output in the grid cell containing each PlioMioVAR site, we used range-normalised root mean square error (NRMSE).

To visualise our data–model comparisons, the model outputs and proxy data are individually transformed into normalised distributions using  $z$ -score normalisation ( $z = (x - \mu)/\sigma$ ), where  $z$  is the  $z$ -score,  $x$  is the model output or proxy value, and  $\mu$  is the mean and  $\sigma$  is the standard deviation calculated across the model grid cells or proxy data points included in the figure for the corresponding dataset. In the model  $z$ -score calculation we use all grid cells in the Atlantic Ocean, excluding the upper 200 m. For the proxy  $z$ -score, we use all the available data from core sites. The mean of each dataset is set to zero and an increment of one represents one standard deviation within that dataset. Data from the top 200 m of the ocean have been excluded from calculating the mean and standard deviation as surface waters are subject to high variability from air–sea exchange and biological productivity that would skew isotopic signatures and would not be representative of the deep ocean patterns. Standardising the climate model output and proxy data using the  $z$ -score method enables comparison of circulation patterns without focusing on absolute values. For example, the climate simulations are not adjusted for changes in  $\delta^{18}\text{O}$  of seawater due to an increase in land ice volume from the mid-Piacenzian to modern, which is recorded in the benthic foraminifera proxy record. While we argue this approach helps us compare the spatial patterns, we acknowledge that this removes information on the magnitude of the spatial variance from the direct comparison.

We use different transects to quantify and evaluate spatial patterns in data and model outputs (Fig. 3). Using the model output, we calculate four mean transects: a zonal mean (an average of grid cells across the Atlantic basin from the South to the North Atlantic), a meridional mean across the equator (an average of grid cells from  $10^\circ\text{N}$  to  $10^\circ\text{S}$  along the equator), and distance–depth cross-sections along the eWOCE A13 and eWOCE A16 transects (both eWOCE transects have a  $10^\circ$  longitudinal band from the transect line; Fig. 3). We then plot the benthic foraminiferal  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values that lie in the associated transect zones for comparison. The zonal mean and eWOCE transects show patterns in  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  that reflect latitudinal water mass distributions and mixing zones. The meridional mean across the equator allows us to examine the horizontal patterns across the Atlantic basin and characterise the differences in water masses between the model and the proxy data.

## 3 Proxy results

The  $\delta^{13}\text{C}$  distribution reveals a distinct spatial pattern across the Atlantic Basin, with more negative values at intermediate depths in the South Atlantic (1000–2000 m water depth, Fig. 4a). The  $\delta^{13}\text{C}$  values of the PlioMioVAR dataset range from  $-0.28\text{‰}$  to  $1.15\text{‰}$ , with a mean of  $0.74\text{‰}$  and a standard deviation of  $0.35\text{‰}$ . Higher values extend from the North Atlantic to the tropics, with the highest  $\delta^{13}\text{C}$  values recorded at ODP Site 927 ( $1.15\text{‰}$ ) on the Ceará Rise in the tropical Atlantic.

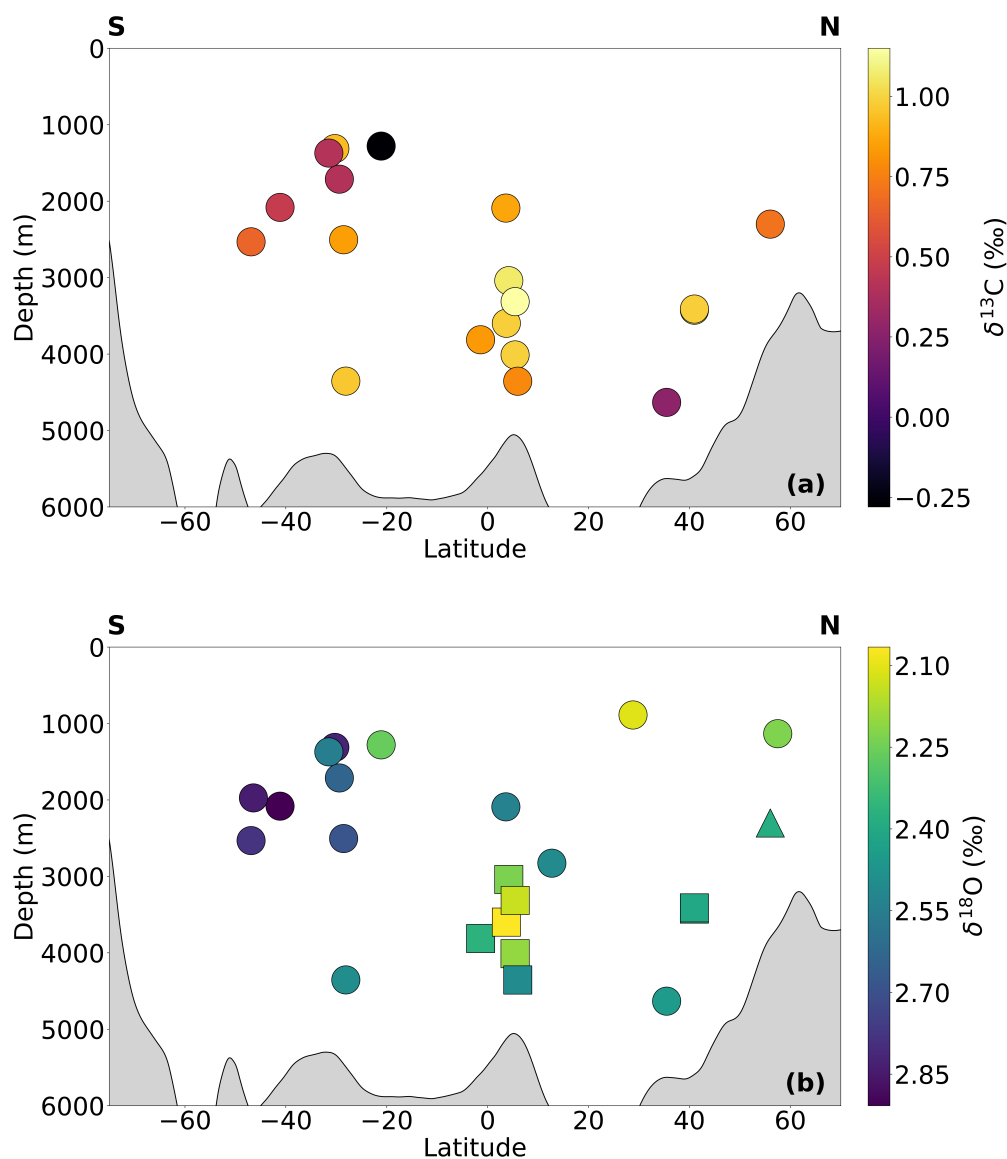


**Figure 4.** Atlantic Ocean mid-Piacenzian KM5c benthic foraminiferal  $\delta^{13}\text{C}$  (a) and  $\delta^{18}\text{O}$  (b) proxy values from PlioMioVAR sites plotted as a latitude–depth cross section from the South Atlantic to North Atlantic for the whole basin (see Fig. 3 for site locations).  $\delta^{13}\text{C}$  values contain only *Cibicidoides* spp. while  $\delta^{18}\text{O}$  includes *Cibicidoides* spp., *Uvigerina* spp. and *Hoeglundina elegans* values that are species-corrected to *Cibicidoides* values (Marchitto et al., 2014). Square markers represent analysis from *Cibicidoides* species only, circle markers represent sites where samples were analysed from both *Cibicidoides* and *Uvigerina* species and triangle markers represent sites where samples were analysed from *Cibicidoides*, *Uvigerina*, and *Hoeglundina* species.

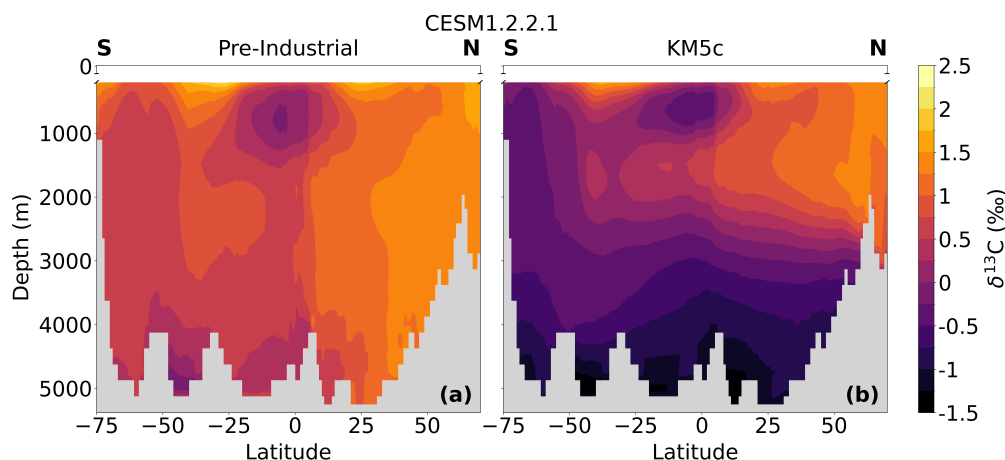


**Figure 5.** Geochemically enabled CESM1.2.2.1  $\delta^{13}\text{C}$  model outputs for the Pre-Industrial (a) and mid-Piacenzian KM5c (b) Atlantic zonal mean. Model parameters described in Table 2.

The lowest value is recorded at South Atlantic ODP Site 1082 ( $-0.28\text{‰}$ ). On the Cear Rise near the equator (ODP Sites 925–929),  $\delta^{13}\text{C}$  values show a vertical gradient, decreasing from  $1.15\text{‰}$  at 3315 m (ODP Site 927) to  $0.78\text{‰}$  at 4356 m (ODP Site 929). We do not find a large difference in the spatial pattern between KM5c (3.225–3.185 Ma) and the PRISM3D interval  
 145 (3.264–3.025 Ma, Fig. A1, Table A3).

The spatial distribution of Atlantic Basin  $\delta^{18}\text{O}$  values during KM5c shows higher  $\delta^{18}\text{O}$  values at intermediate depths in the South Atlantic (1000–2000 m water depth), with lower values in the deeper ocean and North Atlantic (Fig. 4b). The  $\delta^{18}\text{O}$  values range from  $2.07\text{‰}$  to  $2.91\text{‰}$ , with a mean of  $2.46\text{‰}$  and a standard deviation of  $0.24\text{‰}$ . The highest  $\delta^{18}\text{O}$  values were recorded at ODP Site 1088 in the South Atlantic ( $2.91\text{‰}$ ), while the lowest values were observed at ODP Site 926 in the  
 150 equatorial Atlantic ( $2.07\text{‰}$ ). Like the  $\delta^{13}\text{C}$  values reported above, a vertical gradient is seen in  $\delta^{18}\text{O}$  values at the equator, increasing with depth from  $2.07\text{‰}$  at ODP Site 925 (3041 m water depth) to  $2.50\text{‰}$  at ODP Site 929 (4356 m water depth). A distinct latitudinal gradient is evident, with  $\delta^{18}\text{O}$  values approximately  $0.5\text{‰}$  higher in the South Atlantic (ODP Sites 1088, 1092) compared to sites at similar depths in the equatorial and North Atlantic.

The KM5c  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values exhibited similar spatial patterns to Holocene core top  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values, with relatively low variance (Table A2). The overall mean difference for  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  between KM5c and the core tops was low  
 155 ( $<0.2\text{‰}$ ), but there were some large site-specific differences: the KM5c – Holocene difference in  $\delta^{13}\text{C}$  values at North Atlantic DSDP Site 607 ( $-0.60\text{‰}$ ), South Atlantic ODP Site 1267 ( $+0.47\text{‰}$ ), and ODP Site 1085 ( $-0.47\text{‰}$ ); and the KM5c – Holocene difference in  $\delta^{18}\text{O}$  values at South Atlantic ODP Sites 1088 ( $-0.55\text{‰}$ ) and 1092 ( $-0.61\text{‰}$ ).



## 4 Model results

### 160 4.1 $\delta^{13}\text{C}$ -enabled model results

The  $\delta^{13}\text{C}$ -enabled CESM1.2.2.1 model shows higher  $\delta^{13}\text{C}$  values in the shallow North Atlantic and lower  $\delta^{13}\text{C}$  values in the deep Atlantic Ocean and the Southern Ocean during both the Pre-Industrial and KM5c interval (Fig. 5). The  $\delta^{13}\text{C}$  is more stratified in the deep ocean during KM5c relative to Pre-Industrial. In the ocean basin below 1000 m depth, the simulated  $\delta^{13}\text{C}$  values are on average 0.96‰ lower in the KM5c than Pre-Industrial in the CESM1.2.2.1 model, suggesting a secular change  
165 between the two periods. This lower  $\delta^{13}\text{C}$  value is most prominent in the deeper waters, where the difference is upwards of 2‰, while the intermediate ocean  $\delta^{13}\text{C}$  values remained roughly the same.

### 4.2 $\delta^{18}\text{O}$ -enabled model results

#### 4.2.1 $\delta^{18}\text{O}_{\text{seawater}}$

In general, the models simulate high  $\delta^{18}\text{O}_{\text{seawater}}$  values at the surface in subtropical and tropical regions that decrease towards  
170 high latitudes and with depth during both the Pre-Industrial and KM5c intervals (Figs. 6a, d, g and 7a, d, g). This reflects the intense evaporation (high  $\delta^{18}\text{O}_{\text{seawater}}$ ) in (sub)tropical regions and increased precipitation (low  $\delta^{18}\text{O}_{\text{seawater}}$ ) towards higher latitudes. Both of the iCESM1.3 and iCESM1.2-ITPCAS models simulate a high  $\delta^{18}\text{O}_{\text{seawater}}$  deep water mass from the North Atlantic and a low  $\delta^{18}\text{O}_{\text{seawater}}$  water mass at ~500 m water depth and bottom water from the Southern Ocean. The HadCM3 model shows strong latitudinal variability in the  $\delta^{18}\text{O}_{\text{seawater}}$  values, without much vertical variability.

#### 175 4.2.2 Temperature

In the deep ocean, the iCESM1.3 model suggests a temperature field with similar stratification during KM5c and Pre-Industrial, while the iCESM1.2-ITPCAS and HadCM3 model a more stratified ocean in the Pre-Industrial compared to KM5c (Figs. 6b, e, h and 7b, e, h). During KM5c, the HadCM3 model has little change in temperature at depths greater than 1000 m.

#### 4.2.3 Calculated $\delta^{18}\text{O}_{\text{calcite}}$

180 As the models simulate temperature and  $\delta^{18}\text{O}_{\text{seawater}}$ , we have used these outputs to calculate the  $\delta^{18}\text{O}_{\text{calcite}}$  for comparison with the benthic foraminiferal  $\delta^{18}\text{O}_{\text{calcite}}$  records. Model  $\delta^{18}\text{O}_{\text{calcite}}$  is calculated from the simulated  $\delta^{18}\text{O}_{\text{seawater}}$  and temperature fields (Figs. 6c, f, i and 7c, f, i, Eq. (1)). In all three models,  $\delta^{18}\text{O}_{\text{calcite}}$  values are lower in warm waters and higher in cold waters.

### 4.3 Stream function results

185 Three of the four models (iCESM1.3, iCESM1.2-ITPCAS and HadCM3) simulate a stronger Atlantic zonal mean stream function in the Pliocene in comparison to Pre-Industrial (Fig. 8). The models show variable changes in AMOC depth; for instance, iCESM1.3 models a strong, shallow AMOC whereas HadCM3 models a strong, deep AMOC.

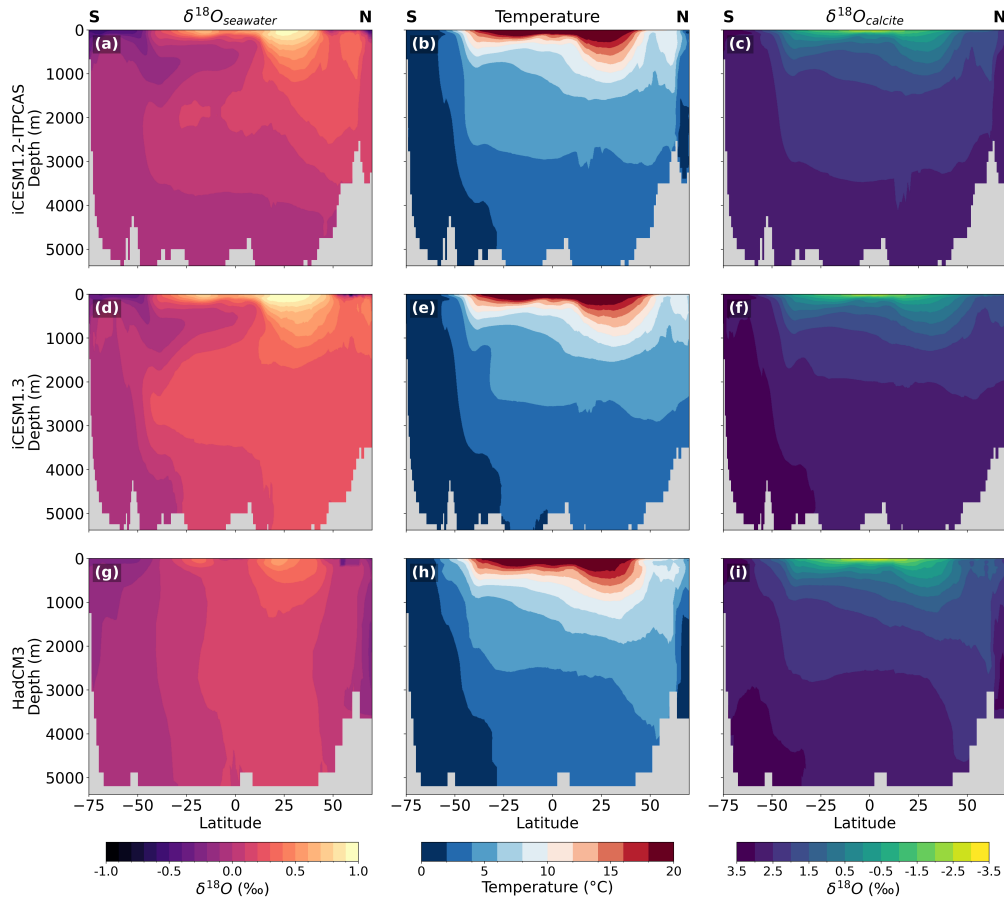


**Figure 6.** Pre-Industrial Atlantic zonal mean of iCESM1.2-ITPCAS (a–c), iCESM1.3 (d–f), and HadCM3 (g–i) with the model  $\delta^{18}\text{O}_{\text{seawater}}$  (a, d, g), temperature outputs (b, e, h) and calculated  $\delta^{18}\text{O}_{\text{calcite}}$  (c, f, i). Model parameters described in Table 2.

## 5 Proxy-based AMOC reconstructions

The PlioMioVAR dataset suggests that NADW, characterised by higher  $\delta^{13}\text{C}$  and lower  $\delta^{18}\text{O}$  values (Peterson et al., 2014; Muglia and Schmittner, 2021; Muglia et al., 2023), extends equatorward and to depths of  $\sim 3000$  m during the KM5c interval (Fig. 4), consistent with previous benthic foraminiferal  $\delta^{13}\text{C}$ -based reconstructions that suggest an enhanced and more expansive Pliocene NADW compared to the Holocene (Raymo et al., 1996; Ravelo and Andreasen, 2000; Frank et al., 2002; Dowsett et al., 2009; Bell et al., 2015). Our interpretations come with the caveats that we have spatially limited data, and that, while  $\delta^{18}\text{O}$  is a conservative tracer (though sea ice formation may influence  $\delta^{18}\text{O}$  values, Toggweiler and Samuels, 1995),  $\delta^{13}\text{C}$  is impacted by surface productivity, vital effects, depositional environment, and possible changes in  $\delta^{13}\text{C}$  end-members of water that subducts in the North and Southern Ocean deep water formation regions (Mackensen et al., 1993; Zhang et al., 2013a; Marchitto et al., 2014). For example, changes in surface ocean productivity in equatorial upwelling regions can influence  $\delta^{13}\text{C}$

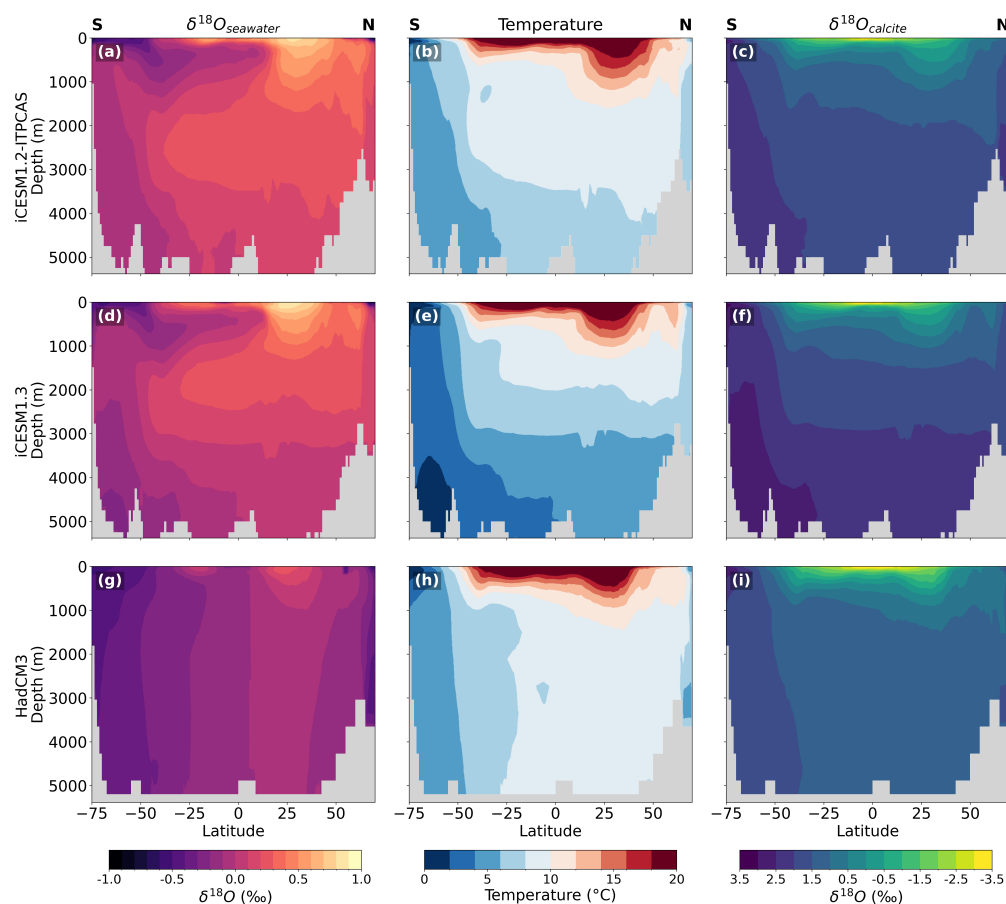


**Figure 7.** Mid-Piacenzian KM5c Atlantic zonal mean of iCESM1.2-ITPCAS (a–c), iCESM1.3 (d–f), and HadCM3 (g–i) with the model  $\delta^{18}\text{O}_{\text{seawater}}$  (a, d, g), temperature outputs (b, e, h) and calculated  $\delta^{18}\text{O}_{\text{calcite}}$  (c, f, i). Model parameters described in Table 2.

values (Bolton et al., 2010a) and highly productive regions, like the Benguela upwelling system, can result in post-depositional processes, such as pore water remineralisation, which can result in lower benthic foraminiferal  $\delta^{13}\text{C}$  values (Bickert and Wefer, 1999).

The benthic foraminiferal records at equatorial sites on the Ceará Rise depth transect suggest a mixture of NADW sources and a deep boundary between NADW and Antarctic Bottom Water (AABW) (Fig. 4). The  $\delta^{18}\text{O}_{\text{calcite}}$  values reverse direction with depth; values decrease from ODP Sites 925, 927 and 926 (2.233, 2.136, 2.066‰ at water depths 3041, 3315, 3598 m respectively) before increasing at ODP Sites 928 and 929 (2.203, 2.504‰ at water depths 4012 and 4356 m respectively). A ternary mixing model based on benthic foraminiferal  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  suggested the presence of two Northern Component Waters (NCW) that form NADW, with a shallower NCW1 having higher  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  than the deeper NCW2 (Van Der Weijst et al., 2020). In this framework, ODP Site 925 and ODP Site 927 appear to have been situated at a depth primarily influenced by NCW1, while ODP Site 926 and deeper locations were bathed in NCW2. The observed decrease in  $\delta^{18}\text{O}$  from ODP Site

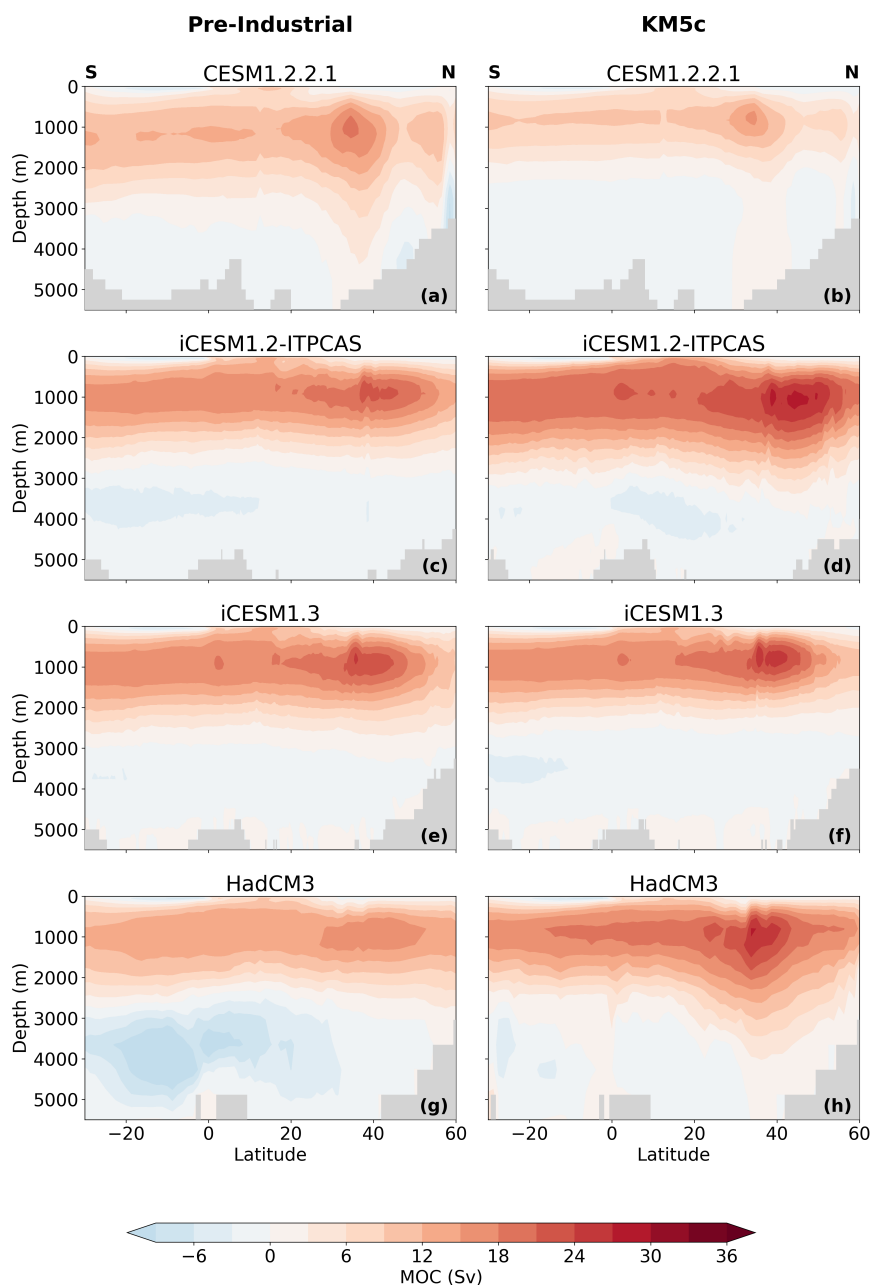


**Figure 8.** Pre-Industrial (a, c, e, g) and KM5c (b, d, f, h) Atlantic zonal mean stream function as a proxy for AMOC strength for CESM1.2.2.1 (a, b), iCESM1.2-ITPCAS (c, d), iCESM1.3 (e, f) and HadCM3 (g, h).



925 to 926 is thus interpreted as a reflection of this transition from the higher  $\delta^{18}\text{O}$  NCW1 to the lower  $\delta^{18}\text{O}$  NCW2. The  
 210  $\delta^{13}\text{C}$  proxies also agree with this interpretation, with ODP Sites 925 and 927 having higher  $\delta^{13}\text{C}$  values than the deeper ODP  
 Site 926 due to the change in water mass. At ODP Site 929, where  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values increase, we interpret the site as  
 lying in a mixing zone between AABW and NADW, as evidenced by the lower temperature and salinity at the site, and thus  
 recording both AABW and NADW signals (Billups et al., 1998). Additional proxy data, such as benthic foraminiferal Mg/Ca  
 to reconstruct bottom-water temperature, would help constrain temperature and  $\delta^{18}\text{O}$  of seawater signals.

215 In the South Atlantic, the benthic foraminiferal  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values suggest that AABW had low  $\delta^{13}\text{C}$  values and high  
 $\delta^{18}\text{O}$  values, but our interpretation is hindered by the lack of Southern Ocean sites at depths greater than 3000 m (Figs. 3 and 4).  
 Unfortunately, the PlioMioVAR dataset does not have a representative AABW site in the Southern Ocean; for example, ODP  
 Site 1267 (Fig. 4), the only site in the deep South Atlantic, is located in the restricted Angola Basin. During the Pleistocene,  $\varepsilon_{\text{Nd}}$   
 values at this site suggest the Walvis Ridge created a bathymetric barrier, resulting in mixing of NADW and AABW (Farmer  
 220 et al., 2019), likely making it an inappropriate site to constrain an AABW.

## 6 Model-based AMOC reconstructions

There is a range of AMOC structures implied by the stable-isotope enabled models (Figs. 5 and 7) and stream functions (Fig. 8),  
 with differences in the extent of simulated NADW and AABW, particularly in the deep North Atlantic. These differences may  
 partly reflect model physics and experimental design. HadCM3 uses a rigid-lid ocean ( $1.25^\circ$ , 20 levels) with a parameterised  
 225 Nordic Seas overflow, whereas the CESM-family models share the free-surface POP2 ocean (nominal  $1^\circ$ , 60 levels) and differ  
 mainly in their atmospheric component and resolution (Hunter et al., 2019; Feng et al., 2020; Sun et al., 2024). Boundary con-  
 ditions also differ in that HadCM3, iCESM1.3 and iCESM1.2-ITPCAS use the PRISM4 enhanced palaeogeography, including  
 a closed Bering Strait and Canadian Arctic Archipelago (Dowsett et al., 2016), while CESM1.2.2.1 retains modern geography  
 with modified cloud properties to reproduce the reduced Pliocene meridional temperature gradient (Burls et al., 2017). Spin-up  
 230 lengths and initialisation also vary between models, so the deep ocean may not be equally equilibrated in each simulation.

$\delta^{13}\text{C}$ -enabled CESM1.2.2.1 suggests NADW is shallow during the Pliocene relative to the Pre-Industrial (Fig. 5). During  
 the Pliocene, CESM1.2.2.1 has a weak AMOC cell (Fig. 8), likely due to the existence of a Pacific Meridional Overturning  
 Circulation in that model (Burls et al., 2017; Baker et al., 2025). For the oxygen isotope-enabled models, the  $\delta^{18}\text{O}_{\text{seawater}}$   
 output from iCESM1.3 and iCESM1.2-ITPCAS show an AMOC structure similar to Pre-Industrial (Figs. 6, 7). HadCM3  
 235 appears unable to resolve NADW for the Pre-Industrial and KM5c in  $\delta^{18}\text{O}_{\text{seawater}}$  space, though an AMOC is clearly present  
 in the stream function (Fig. 8). Zhang et al. (2021) found a wide range in simulated AMOC strength and spatial extent in the  
 PlioMIP2 models, which is also seen in the isotope-enabled models' stream functions. The isotope-enabled models appear to  
 have different skill in matching the overturning circulation pattern shown by the stream functions; this suggests isotope systems  
 may be overwritten by other processes (e.g. mixing, respiration) and this influences our ability to infer water mass structure in  
 240 the isotope models and perhaps proxy data.

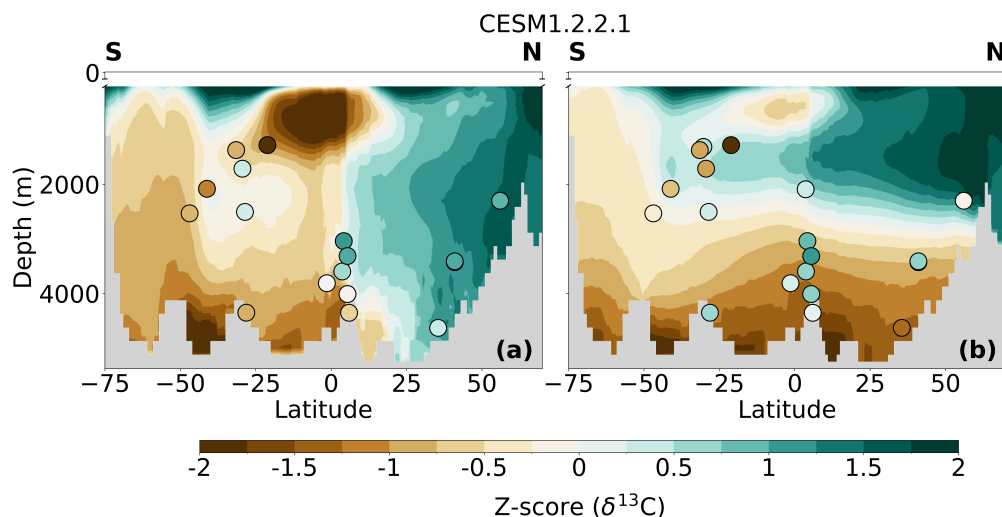


**Figure 9.** Z-score normalised climate model output and benthic foraminiferal  $\delta^{13}\text{C}$  values. The mean of each dataset is set to zero and an increment of one represents one standard deviation within that dataset. Background is contoured Pre-Industrial (a) and mid-Piacenzian KM5c (b) Atlantic zonal mean  $\delta^{13}\text{C}$ -enabled CESM1.2.2.1 model output with benthic foraminiferal  $\delta^{13}\text{C}$  values overlain (circles).

Although  $\delta^{18}\text{O}_{\text{calcite}}$  values are influenced by both  $\delta^{18}\text{O}_{\text{seawater}}$  and temperature (Eq. (1)), global temperature distribution imparts a larger signal on  $\delta^{18}\text{O}_{\text{calcite}}$  because temperature has a larger range than  $\delta^{18}\text{O}_{\text{seawater}}$  (Figs. 6 and 7,  $0.22\text{‰} \simeq 1\text{ °C}$ ). This results in the calculated  $\delta^{18}\text{O}_{\text{calcite}}$  values reflecting mostly temperature. For instance, although Antarctic Intermediate Water (AAIW) has a distinct  $\delta^{18}\text{O}_{\text{seawater}}$  signature in the modern ocean (LeGrande and Schmidt, 2006; Reagan et al., 2023) as well as in the modelled  $\delta^{18}\text{O}_{\text{seawater}}$  for KM5c and Pre-Industrial simulations, regional temperature imparts a stronger influence on  $\delta^{18}\text{O}_{\text{calcite}}$  such that AAIW does not appear as a distinct water mass in  $\delta^{18}\text{O}_{\text{calcite}}$ ; this implies  $\delta^{18}\text{O}_{\text{calcite}}$  may not be a sufficient water mass tracer on its own, but may help interpretations within a multi-proxy framework.

## 7 Exploring the data–model agreement and mismatch

Stable isotopes of benthic foraminifera have long been used as a proxy for deep ocean circulation and water mass properties (Raymo et al., 1996; Ravelo and Andreasen, 2000; Curry and Oppo, 2005; Lisiecki, 2014), though there are a number of factors that can influence this interpretation (productivity, vital effects, depositional environment, possible changes in  $\delta^{13}\text{C}$  end-members in the North Atlantic and/or Southern Ocean and brine rejection; Mackensen et al., 1993; Toggweiler and Samuels, 1995; Zhang et al., 2013a; Marchitto et al., 2014). In Figs. 9 and 10, we compare z-score normalised spatially explicit proxy data to the Atlantic zonal mean of the climate model output. Taken at face value, the benthic foraminiferal  $\delta^{13}\text{C}$  values suggest mid-Piacenzian KM5c NADW is similar to and/or more extensive than today, whereas  $\delta^{13}\text{C}$ -enabled CESM1.2.2.1 shows a less expansive NADW. For  $\delta^{18}\text{O}_{\text{calcite}}$ , the benthic foraminiferal  $\delta^{18}\text{O}$  values are lower in the deep Atlantic ( $>3000\text{ m}$ ) and higher in the mid-depth South Atlantic ( $\sim 2000\text{ m}$ ) in comparison to the modelled values for KM5c. The Pre-Industrial shows

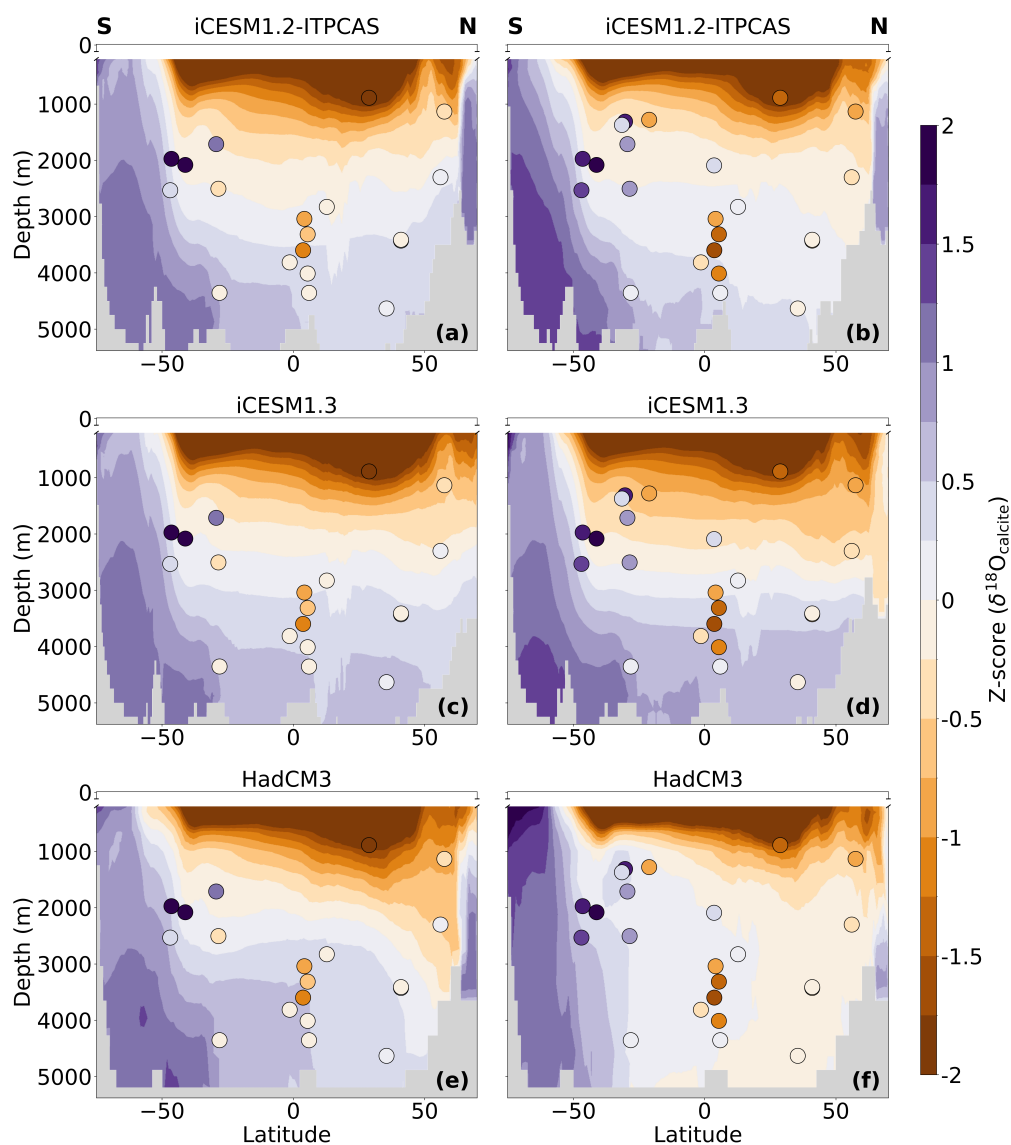


**Figure 10.** Z-score normalised climate model output and benthic foraminiferal  $\delta^{18}\text{O}$  values. The mean of each dataset is set to zero and an increment of one represents one standard deviation within that dataset. Background is contoured Pre-Industrial (a, c, e) or mid-Piacenzian KM5c (b, d, f) Atlantic zonal mean  $\delta^{18}\text{O}_{\text{calcite}}$  calculated from model output for iCESM1.2-ITPCAS, iCESM1.3 and HadCM3 and benthic foraminiferal  $\delta^{18}\text{O}$  values overlain (circles).

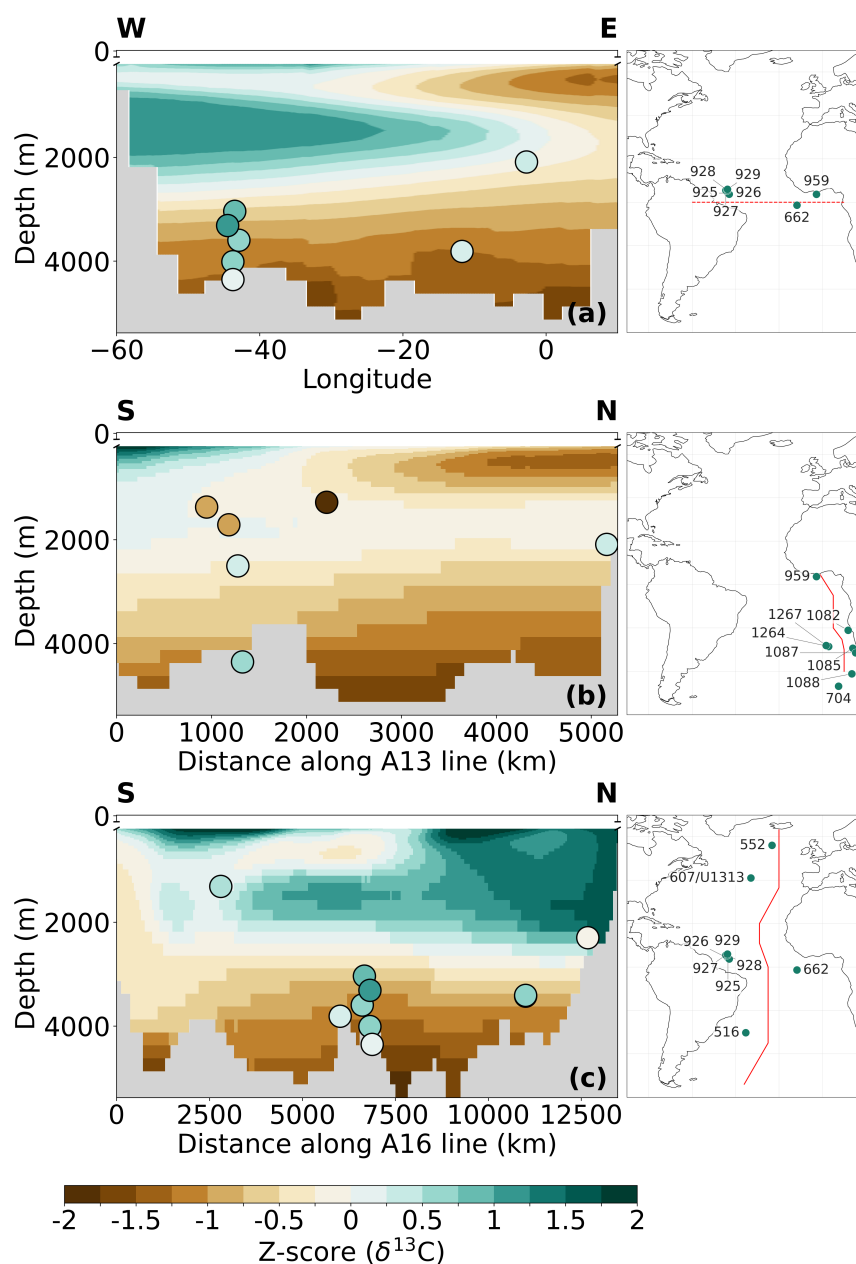


**Figure 11.** Z-score normalised climate model output and benthic foraminiferal  $\delta^{13}\text{C}$  values for the mid-Piacenzian KM5c. The mean of each dataset is set to zero and an increment of one represents one standard deviation within that dataset. Background is contoured  $\delta^{13}\text{C}$ -enabled CESM1.2.2.1 model output with benthic foraminiferal  $\delta^{13}\text{C}$  values overlain (circles) for meridional mean across the equator (a), eWOCE A13 transect (b) and eWOCE A16 (c). See Fig. 3 for further detail on site information.

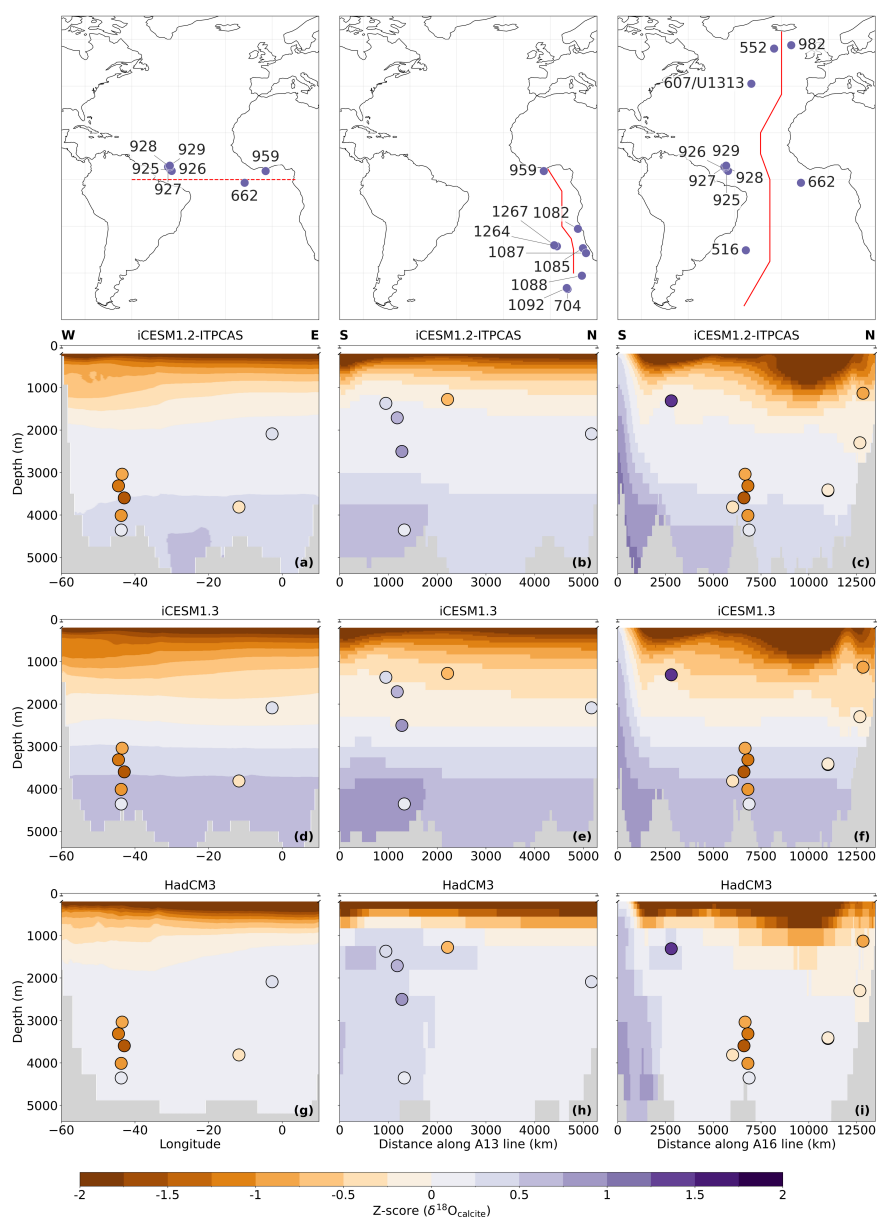


**Figure 12.** Z-score normalised climate model output and benthic foraminiferal  $\delta^{18}\text{O}$  values for the mid-Piacenzian KM5c. The mean of each dataset is set to zero and an increment of one represents one standard deviation within that dataset. Background is contoured  $\delta^{18}\text{O}$  model output for meridional mean across the equator (a, d, g), eWOCE A13 (b, e, h) and eWOCE A16 (c, f, i)  $\delta^{18}\text{O}_{\text{calcite}}$  calculated from model output for iCESM1.2-ITPCAS, iCESM1.3 and HadCM3 and benthic foraminiferal  $\delta^{18}\text{O}$  values overlain (circles). See Fig. 3 for further detail on site information.



poor spatial agreement between the model and proxy data, suggesting a poor data–model match in general (Fig. 10). A site-by-site comparison of the benthic foraminiferal  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values and corresponding model grid cell outputs is presented in  
 260 Tables A4 and A5 and Figs. A2 and A3. A comparison of the means and standard deviations used in the z-score are presented in Table A6. The NRMSE values show there is poor data–model spatial pattern match. The  $\delta^{13}\text{C}$  data and  $\delta^{13}\text{C}$ -enabled CESM1.2.2.1 model have an NRMSE of 0.716. The  $\delta^{18}\text{O}_{\text{calcite}}$  data and model outputs also show poor spatial agreement, quantified by high NRMSE values (1.26, 1.40, 0.83 for iCESM1.2-ITPCAS, iCESM1.3 and HadCM3 respectively).

While equatorial western Atlantic sites at mid-depth on the Ceará Rise (ODP Sites 926 and 927) show signs of NADW  
 265 influence in the benthic foraminiferal  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}_{\text{calcite}}$  values, this is generally not seen in the modelled Atlantic  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}_{\text{calcite}}$  (Figs. 9 and 10). In Figs. 11 and 12, we compare z-score normalised model output and proxy data ( $\pm 10^\circ$  latitude and longitude) along the meridional mean across the equator and the eWOCE A13 and A16 transects. At the Ceará Rise, where the model bathymetry reasonably approximates the true seafloor depth, CESM1.2.2.1, iCESM1.3, and iCESM1.2-ITPCAS show a shoaling of NADW which conflicts with benthic foraminiferal  $\delta^{13}\text{C}$  signatures that imply sustained NADW  
 270 prominence during the mid-Piacenzian KM5c (Raymo et al., 1996; Ravelo and Andreasen, 2000; Frank et al., 2002; Dowsett et al., 2009). This data–model mismatch may be due to 1) the models underestimating northern deep-water formation (Hirschi et al., 2020; Oliveira Matos et al., 2025), 2) changes in the  $\delta^{13}\text{C}$  end-member in the North Atlantic and/or Southern Ocean (Zhang et al., 2013b), and/or 3) local biogeochemical processes overprinting the water mass signal in the benthic foraminiferal  $\delta^{13}\text{C}$  records (Bickert and Wefer, 1999; Ravelo and Hillaire-Marcel, 2007; Bolton et al., 2010a). For instance, the strong data–  
 275 model mismatch at ODP Site 1082 may be due to pore water remineralisation impacting benthic foraminiferal  $\delta^{13}\text{C}$  values in the Benguela upwelling zone (Bickert and Wefer, 1999).

The negative benthic foraminiferal  $\delta^{13}\text{C}$  values from the eastern and western South Atlantic (Fig. 4) suggest AAIW may have been deeper during KM5c relative to today ( $\sim 2500$  m vs 1000 to 1500 m water depth today). A study using eastern South Atlantic DSDP Site 516 suggests AAIW was warmer and saltier during the Pliocene relative to today (Karas et al., 2019). As  
 280 this area in the South Atlantic along the Polar Front is a mixing zone of AAIW, NADW, Circumpolar Deep Water (CDW) and AABW (Talley, 2013; Liu and Tanhua, 2021; Sun et al., 2025), this suggests the AMOC mixing zone may have been different in physical properties and spatial pattern during KM5c. In the South Atlantic, the positive benthic foraminiferal  $\delta^{18}\text{O}_{\text{calcite}}$  values are shifted approximately  $10^\circ$  equatorward in comparison to the steep  $\delta^{18}\text{O}_{\text{calcite}}$  gradient simulated by the models (i.e. the cluster of dark intermediate depth circles and the near vertical  $\delta^{18}\text{O}_{\text{calcite}}$  gradient from the models, Fig. 10). This  
 285 data–model mismatch is not due to the majority of proxy site locations being in the western Atlantic basin in comparison to the zonal mean of the models (Fig. 12). A possible explanation is the models are simulating frontal systems too close to the polar region relative to what the benthic foraminiferal  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values suggest.

We find the choice of time interval (i.e. the  $\sim 20$  kyr KM5c interval versus the  $\sim 200$  kyr PRISM3D interval) does not reconcile previous data–model mismatch (Fig. 4, Fig. A1) (Haywood et al., 2016; Zhang et al., 2021). Patterns in  $\delta^{13}\text{C}$  and  
 290  $\delta^{18}\text{O}$  for the KM5c interval are largely similar to those of the PRISM3D interval, with the exception of slightly higher  $\delta^{13}\text{C}$  values at the sites on the Ceará Rise (ODP Sites 925–929, Table A3, Fig. A1) in KM5c compared to PRISM3D. PlioMIP1 models simulated a warmer mPWP climate compared to Pre-Industrial levels (Haywood et al., 2013); however, the models



generally underestimated high-latitude warming and had a wide inter-model spread in AMOC strength and pattern (Fig. 1; Zhang et al., 2013b). It was suggested that part of this data–model mismatch might be attributed to the use of the PRISM3D reconstruction, where proxies were averaged over a  $\sim 260$ – $300$  kyr window that encompasses orbital environmental variations, making them unsuitable for direct comparison with model outputs which simulate a specific orbital configuration (Haywood et al., 2016). Differences in ocean gateways may also contribute to these issues (Otto-Bliesner et al., 2017; Zhang et al., 2021). PlioVAR to PlioMIP2 surface comparisons addressed this by focusing on the KM5c, a well-defined interglacial period (Haywood et al., 2016). Here we show that even with a more precise timeframe, mismatches in the deep ocean remain between the model and the proxy data for isotope enabled models (Figs. 9 and 10, Figs. A2 and A3).

## 8 Conclusions

We assessed the capabilities of the benthic foraminiferal  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values and four multi-system isotope-enabled climate models in simulating  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  distribution and patterns in the deep Atlantic Ocean. Our comparison of model and proxy  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  data reveals a persistent data–model mismatch. Proxy data suggest a more expansive and deeper NADW during the mPWP relative to the Holocene, with broader influence across the Atlantic basin, including mixing zones with Antarctic water masses. CESM models generally exhibited a shallow AMOC and different spatial patterns of water masses relative to modern. HadCM3 did not simulate the proxy deep water mass  $\delta^{18}\text{O}$  patterns and instead simulated vertical gradients in  $\delta^{18}\text{O}$  values. Possible limitations on the model reconstructions include uncertainties in model physics, boundary conditions and/or imperfect deep ocean equilibration (e.g. model run time, Stepanek and Lohmann, 2012; Stepanek et al., 2020), particularly concerning deep ocean processes and the formation/mixing of water masses like NADW and AABW, which prevent accurate simulations of Pliocene deep-water circulation due to computational constraints and therefore limited model-integration times. We note that this study relies on the derivation of  $\delta^{18}\text{O}_{\text{calcite}}$  from modelled temperature and  $\delta^{18}\text{O}_{\text{seawater}}$  data; the biases inherent in one parameter could result in non-linear errors that may not be easily detected. Additionally, interpreting the  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values of benthic foraminifera as water mass tracers when multiple other factors (productivity, vital effects, depositional environment, and possible changes in  $\delta^{13}\text{C}$  end-members in the North Atlantic and/or Southern Ocean) may influence  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values has its limitations. Future studies could address such issues by utilising independent temperature proxies like Mg/Ca and/or clumped isotopes for coupled  $\delta^{18}\text{O}$ –temperature data (Elderfield et al., 2012; Ford and Raymo, 2020), other independent water mass tracers, a more widespread distribution of sites, and more polar sites to constrain  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  end-members. Concerns regarding  $\delta^{13}\text{C}$  related to depositional environment and vital effects may be mitigated through the adoption of multi-proxy solutions (Blaser et al., 2025).



## Appendix A: Supplementary data

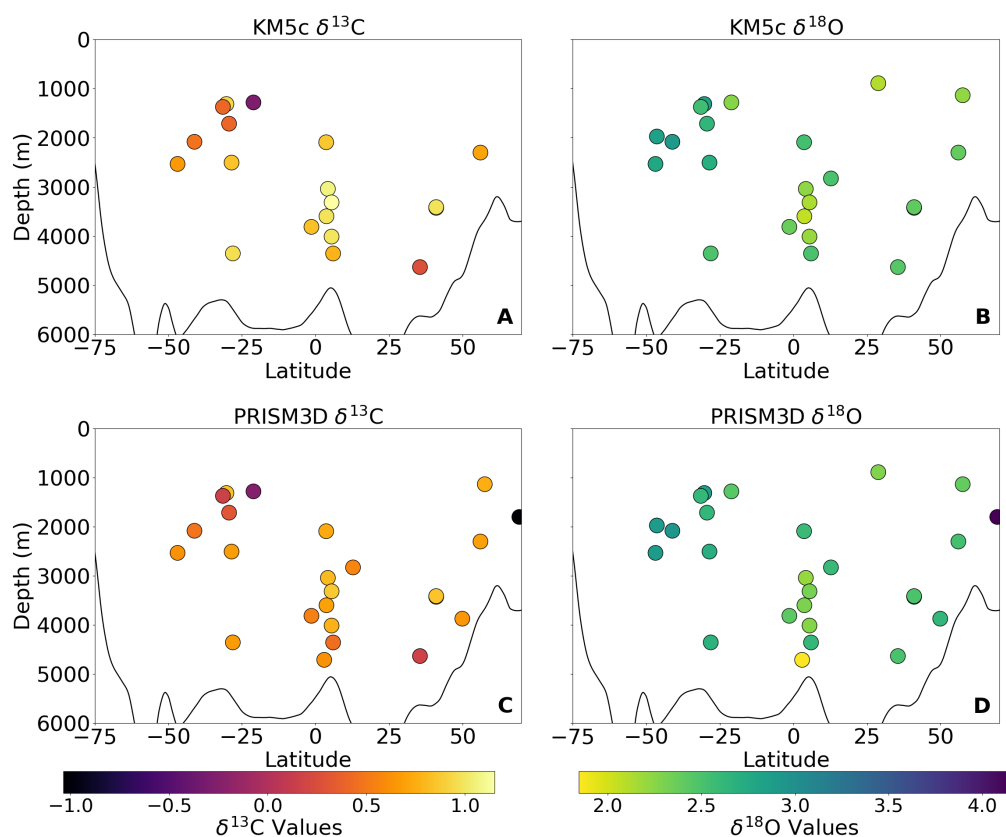


**Figure A1.** PRISM3D (3.264–3.025 Ma) and KM5c (3.225–3.185 Ma)  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  data.

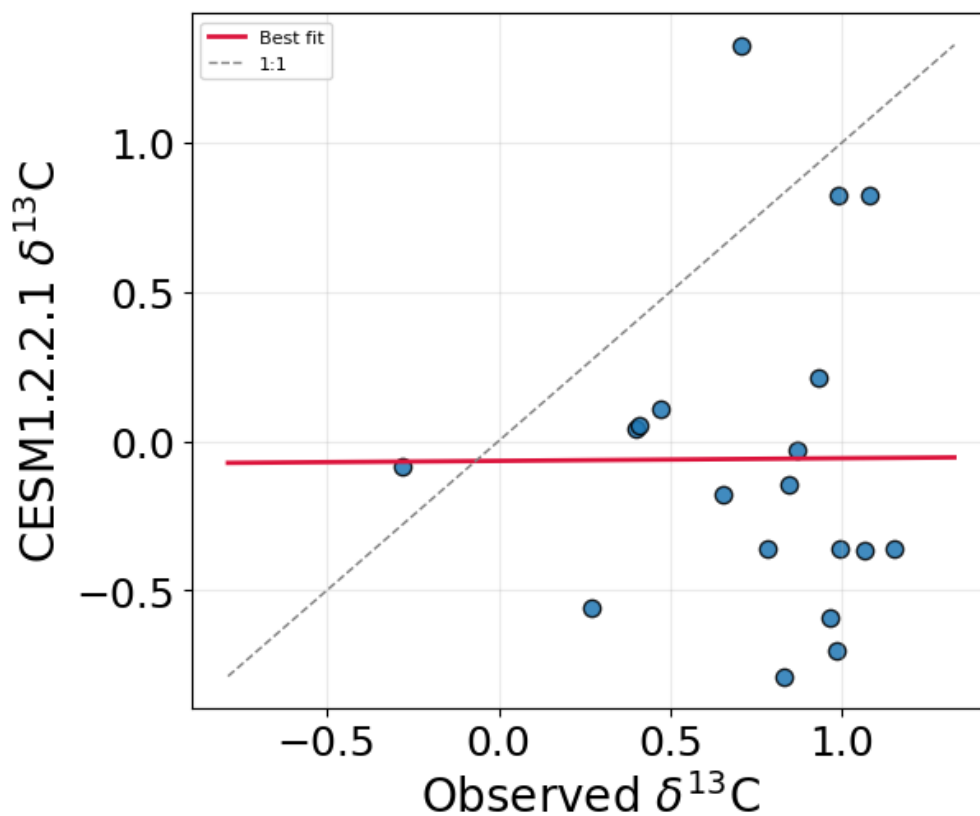


**Figure A2.** Scatter plot of modelled  $\delta^{13}\text{C}$  against PlioMioVAR  $\delta^{13}\text{C}$  values.

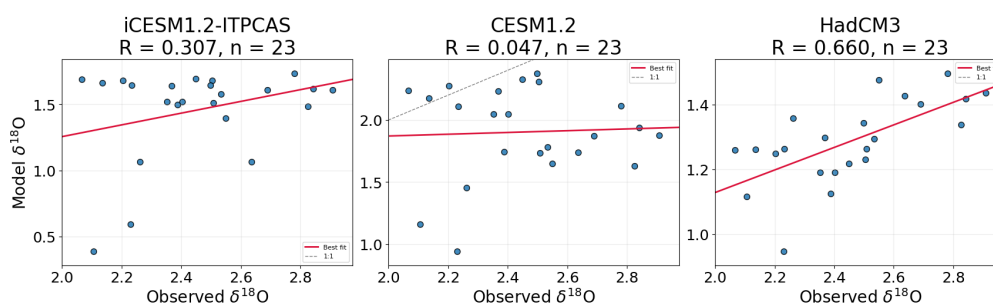


**Figure A3.** Scatter plot of modelled  $\delta^{18}\text{O}_{\text{calcite}}$  against PlioMioVAR  $\delta^{18}\text{O}$  values.



**Table A1.** PlioMioVAR and OC3  $\delta^{18}\text{O}$  comparison. The site matching algorithm categorises how OC3 data points are linked to PlioMioVAR sites. “Conservative” matching uses a spatial buffer of  $\delta d = 500$  km and  $\delta z = z/10$  (where  $z$  is depth from the surface). “Liberal” matching uses a buffer of  $\delta d = 1000$  km and  $\delta z = z/5$ . “+ self” indicates that PlioMioVAR core sites with core top data less than 6000 years old were also included as Pre-Industrial data points in the anomaly calculation.

| Site name | OC3 matches | PlioMioVAR $\delta^{18}\text{O}$ | OC3 $\delta^{18}\text{O}$ | Site matching algorithm | PlioMioVAR anomaly | PlioMioVAR taxa                           |
|-----------|-------------|----------------------------------|---------------------------|-------------------------|--------------------|-------------------------------------------|
| 516       | 0           | 2.83                             | –                         | N/A                     | –                  | <i>Cibicoides</i>                         |
| 552       | 5           | 2.39                             | 2.69                      | conservative + self     | –0.30              | <i>Cibicoides, Uvigerina, Hoeglundina</i> |
| 603       | 1           | 2.45                             | 2.70                      | liberal                 | –0.25              | <i>Cibicoides</i>                         |
| 607       | 1           | 2.35                             | 2.68                      | conservative            | –0.33              | <i>Cibicoides, Uvigerina</i>              |
| 625       | 3           | 2.11                             | 1.78                      | liberal                 | 0.33               | <i>Cibicoides</i>                         |
| 662       | 2           | 2.37                             | 2.54                      | conservative            | –0.17              | <i>Cibicoides, Uvigerina</i>              |
| 704       | 1           | 2.78                             | 2.76                      | conservative            | 0.02               | <i>Cibicoides</i>                         |
| 925       | 3           | 2.23                             | 2.29                      | conservative + self     | –0.06              | <i>Cibicoides, Uvigerina</i>              |
| 926       | 2           | 2.07                             | 2.23                      | conservative            | –0.17              | <i>Cibicoides, Uvigerina</i>              |
| 927       | 3           | 2.14                             | 2.36                      | conservative + self     | –0.22              | <i>Cibicoides, Uvigerina</i>              |
| 928       | 3           | 2.20                             | 2.60                      | conservative            | –0.39              | <i>Cibicoides, Uvigerina</i>              |
| 929       | 2           | 2.50                             | 2.55                      | conservative + self     | –0.04              | <i>Cibicoides, Uvigerina</i>              |
| 959       | 0           | 2.53                             | –                         | N/A                     | –                  | <i>Cibicoides</i>                         |
| 982       | 2           | 2.23                             | 2.51                      | conservative            | –0.28              | <i>Cibicoides</i>                         |
| 999       | 2           | 2.51                             | 2.62                      | conservative            | –0.12              | <i>Cibicoides</i>                         |
| 1082      | 0           | 2.26                             | –                         | N/A                     | –                  | <i>Cibicoides</i>                         |
| 1085      | 3           | 2.64                             | 3.06                      | liberal                 | –0.42              | <i>Cibicoides</i>                         |
| 1087      | 0           | 2.55                             | –                         | N/A                     | –                  | <i>Cibicoides</i>                         |
| 1088      | 2           | 2.91                             | 3.46                      | conservative            | –0.55              | <i>Cibicoides</i>                         |
| 1092      | 2           | 2.84                             | 3.46                      | liberal                 | –0.61              | <i>Cibicoides</i>                         |
| 1264      | 3           | 2.69                             | 2.50                      | liberal + self          | 0.19               | <i>Cibicoides</i>                         |
| 1267      | 8           | 2.50                             | 2.57                      | liberal + self          | –0.07              | <i>Cibicoides</i>                         |
| U1313     | 2           | 2.40                             | 2.61                      | conservative            | –0.20              | <i>Cibicoides, Uvigerina</i>              |



**Table A2.** PlioMioVAR and OC3 *Cibicidoides*  $\delta^{13}\text{C}$  comparison. The site matching algorithm categorises how OC3 data points are linked to PlioMioVAR sites. “Conservative” matching uses a spatial buffer of  $\delta d = 500$  km and  $\delta z = z/10$  (where  $z$  is depth from the surface). “Liberal” matching uses a buffer of  $\delta d = 1000$  km and  $\delta z = z/5$ .

| Site name | OC3 matches | PlioMioVAR $\delta^{13}\text{C}$ | OC3 $\delta^{13}\text{C}$ | Site matching algorithm | PlioMioVAR anomaly |
|-----------|-------------|----------------------------------|---------------------------|-------------------------|--------------------|
| 516       | 0           | 0.93                             | –                         | N/A                     | –                  |
| 552       | 8           | 0.71                             | 1.05                      | conservative + self     | –0.34              |
| 603       | 4           | 0.27                             | 0.87                      | liberal                 | –0.60              |
| 607       | 2           | 1.08                             | 1.10                      | conservative            | –0.02              |
| 662       | 4           | 0.83                             | 0.75                      | conservative            | 0.08               |
| 704       | 5           | 0.66                             | 0.51                      | conservative            | 0.15               |
| 925       | 8           | 1.06                             | 1.10                      | conservative + self     | –0.04              |
| 926       | 9           | 0.98                             | 0.93                      | conservative            | 0.05               |
| 927       | 10          | 1.15                             | 1.07                      | conservative + self     | 0.08               |
| 928       | 9           | 0.99                             | 0.73                      | conservative            | 0.26               |
| 929       | 7           | 0.78                             | 0.58                      | conservative + self     | 0.20               |
| 959       | 0           | 0.87                             | –                         | N/A                     | –                  |
| 1082      | 4           | –0.28                            | 0.04                      | conservative            | –0.32              |
| 1085      | 1           | 0.40                             | 0.87                      | conservative            | –0.47              |
| 1087      | 3           | 0.41                             | 0.50                      | conservative            | –0.09              |
| 1088      | 4           | 0.47                             | 0.41                      | conservative            | 0.06               |
| 1264      | 4           | 0.85                             | 0.85                      | liberal + self          | –0.01              |
| 1267      | 11          | 0.96                             | 0.49                      | liberal + self          | 0.47               |
| U1313     | 3           | 0.99                             | 1.07                      | conservative            | –0.08              |



**Table A3.** PRISM3D (3.264–3.025 Ma) and KM5c (3.225–3.185 Ma)  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  data.

| Site name | $\delta^{13}\text{C}$ |       | $\delta^{18}\text{O}$ |      |
|-----------|-----------------------|-------|-----------------------|------|
|           | PRISM3D               | KM5c  | PRISM3D               | KM5c |
| 516       | 0.83                  | 0.93  | 2.86                  | 2.83 |
| 552       | 0.69                  | 0.71  | 2.53                  | 2.39 |
| 603       | 0.16                  | 0.27  | 2.50                  | 2.45 |
| 607       | 0.86                  | 1.08  | 2.52                  | 2.35 |
| 625       | –                     | –     | 2.28                  | 2.11 |
| 662       | 0.54                  | 0.83  | 2.43                  | 2.37 |
| 665       | 0.63                  | –     | 1.85                  | 2.78 |
| 704       | 0.63                  | 0.66  | 2.89                  | –    |
| 907       | –1.04                 | –     | 4.15                  | 2.23 |
| 925       | 0.80                  | 1.07  | 2.21                  | 2.07 |
| 926       | 0.69                  | 0.99  | 2.30                  | 2.14 |
| 927       | 0.87                  | 1.15  | 2.32                  | 2.20 |
| 928       | 0.77                  | 0.99  | 2.27                  | 2.50 |
| 929       | 0.44                  | 0.78  | 2.61                  | 2.53 |
| 959       | 0.73                  | 0.87  | 2.59                  | 2.23 |
| 982       | 0.75                  | –     | 2.40                  | 2.51 |
| 999       | 0.57                  | –     | 2.60                  | 2.26 |
| 1082      | –0.25                 | –0.28 | 2.45                  | 2.64 |
| 1085      | 0.31                  | 0.40  | 2.63                  | 2.55 |
| 1087      | 0.16                  | 0.41  | 2.62                  | 2.91 |
| 1088      | 0.48                  | 0.47  | 2.94                  | –    |
| 1092      | –                     | –     | 2.90                  | 2.84 |
| 1264      | 0.67                  | 0.85  | 2.70                  | 2.69 |
| 1267      | 0.67                  | 0.96  | 2.67                  | 2.50 |
| U1308     | 0.64                  | –     | 2.63                  | –    |
| U1313     | 0.85                  | 0.99  | 2.50                  | 2.40 |



**Table A4.** PlioMioVAR  $\delta^{18}\text{O}$  data with iCESM1.2-ITPCAS, iCESM1.3, and HadCM3 model outputs, where the anomaly is the difference between the mid-Pliocene and Pre-Industrial.

| Site name | PlioMioVAR $\delta^{18}\text{O}$ | iCESM1.2-ITPCAS                         |         | iCESM1.3                                |         | HadCM3                                  |         |
|-----------|----------------------------------|-----------------------------------------|---------|-----------------------------------------|---------|-----------------------------------------|---------|
|           |                                  | $\delta^{18}\text{O}_{\text{seawater}}$ | anomaly | $\delta^{18}\text{O}_{\text{seawater}}$ | anomaly | $\delta^{18}\text{O}_{\text{seawater}}$ | anomaly |
| 516       | 2.83                             | 0.06                                    | 0.10    | 0.06                                    | 0.00    | −0.23                                   | −0.28   |
| 552       | 2.39                             | 0.30                                    | 0.08    | 0.25                                    | −0.03   | −0.13                                   | −0.18   |
| 603       | 2.45                             | 0.18                                    | 0.19    | 0.04                                    | −0.20   | −0.10                                   | −0.23   |
| 607       | 2.35                             | 0.28                                    | 0.16    | 0.15                                    | −0.13   | −0.10                                   | −0.17   |
| 625       | 2.11                             | 0.32                                    | 0.22    | 0.30                                    | 0.07    | 0.01                                    | −0.32   |
| 662       | 2.37                             | 0.22                                    | 0.22    | 0.07                                    | −0.10   | −0.18                                   | −0.28   |
| 704       | 2.78                             | 0.12                                    | 0.11    | 0.10                                    | −0.03   | −0.30                                   | −0.26   |
| 925       | 2.23                             | 0.22                                    | 0.18    | 0.13                                    | −0.10   | −0.08                                   | −0.22   |
| 926       | 2.07                             | 0.19                                    | 0.19    | 0.07                                    | −0.13   | −0.08                                   | −0.22   |
| 927       | 2.14                             | 0.21                                    | 0.19    | 0.10                                    | −0.11   | −0.08                                   | −0.22   |
| 928       | 2.20                             | 0.20                                    | 0.20    | 0.05                                    | −0.15   | −0.08                                   | −0.22   |
| 929       | 2.50                             | 0.20                                    | 0.20    | 0.04                                    | −0.15   | −0.08                                   | −0.22   |
| 959       | 2.53                             | 0.23                                    | 0.18    | 0.27                                    | 0.01    | −0.19                                   | −0.28   |
| 982       | 2.23                             | 0.52                                    | 0.18    | 0.43                                    | 0.01    | −0.08                                   | −0.20   |
| 999       | 2.51                             | 0.27                                    | 0.25    | 0.27                                    | −0.03   | −0.05                                   | −0.26   |
| 1082      | 2.26                             | −0.00                                   | 0.03    | 0.08                                    | −0.01   | −0.23                                   | −0.29   |
| 1085      | 2.64                             | −0.05                                   | −0.08   | 0.23                                    | 0.03    | −0.27                                   | −0.29   |
| 1087      | 2.55                             | 0.00                                    | 0.03    | 0.12                                    | 0.02    | −0.28                                   | −0.29   |
| 1088      | 2.91                             | 0.15                                    | 0.12    | 0.17                                    | 0.02    | −0.30                                   | −0.28   |
| 1092      | 2.84                             | 0.11                                    | 0.10    | 0.13                                    | −0.01   | −0.29                                   | −0.25   |
| 1264      | 2.69                             | 0.20                                    | 0.14    | 0.23                                    | −0.02   | −0.25                                   | −0.30   |
| 1267      | 2.50                             | 0.20                                    | 0.21    | −0.01                                   | −0.09   | −0.26                                   | −0.30   |
| U1313     | 2.40                             | 0.28                                    | 0.16    | 0.15                                    | −0.13   | −0.10                                   | −0.17   |



**Table A5.** PlioMioVAR  $\delta^{13}\text{C}$  data with CESM1.2.2.1 model outputs, where the anomaly is the difference between the mid-Pliocene and Pre-Industrial.

| Site name | PlioMioVAR $\delta^{13}\text{C}$ | CESM1.2.2.1           |         |
|-----------|----------------------------------|-----------------------|---------|
|           |                                  | $\delta^{13}\text{C}$ | anomaly |
| 516       | 0.93                             | 0.21                  | −0.50   |
| 552       | 0.71                             | 1.33                  | −0.02   |
| 603       | 0.27                             | −0.56                 | −1.88   |
| 607       | 1.08                             | 0.82                  | −0.52   |
| 662       | 0.83                             | −0.79                 | −1.31   |
| 704       | 0.66                             | −0.18                 | −0.84   |
| 925       | 1.06                             | −0.37                 | −1.58   |
| 926       | 0.98                             | −0.70                 | −1.87   |
| 927       | 1.15                             | −0.36                 | −1.59   |
| 928       | 0.99                             | −0.36                 | −1.59   |
| 929       | 0.78                             | −0.36                 | −1.59   |
| 959       | 0.87                             | −0.03                 | −0.35   |
| 1082      | −0.28                            | −0.09                 | −0.40   |
| 1085      | 0.40                             | 0.04                  | −0.53   |
| 1087      | 0.41                             | 0.05                  | −0.65   |
| 1088      | 0.47                             | 0.11                  | −0.68   |
| 1264      | 0.85                             | −0.14                 | −0.80   |
| 1267      | 0.96                             | −0.59                 | −1.16   |
| U1313     | 0.99                             | 0.82                  | −0.52   |

**Table A6.** Summary statistics for whole-ocean modelled datasets (units: ‰).

| Dataset                                                    | Mean   | Standard deviation |
|------------------------------------------------------------|--------|--------------------|
| CESM1.2.2.1 ( $\delta^{13}\text{C}$ )                      | 0.8865 | 0.9681             |
| iCESM1.2-ITPCAS ( $\delta^{18}\text{O}_{\text{calcite}}$ ) | 0.9665 | 1.7580             |
| iCESM1.3 ( $\delta^{18}\text{O}_{\text{calcite}}$ )        | 0.9737 | 1.8748             |
| HadCM3 ( $\delta^{18}\text{O}_{\text{calcite}}$ )          | 0.7570 | 2.0339             |



*Code and data availability.* All data will be deposited in the World Data Center PANGAEA repository (<https://www.pangaea.de>) and will be made publicly available when the paper is accepted and a DOI is issued. Code will be deposited on Zenodo.

325 *Author contributions.* Conceptualisation: HLF conceived the study and HED co-designed the study. HED completed all statistical analyses and generated plots with input from HLF. NB, TD, RF, AH, YS, CT, and JT contributed modelling output and advised on analyses. HLF, ELM, and SLH coordinated PlioVAR and PlioMioVAR data curation and quality control. SG and PM provided training and advice on data–model comparison. JA, MA-G, PA, MB, AC, FdG, SDS, CK, KL, BP, ASR, BR, GEAS, CS, DT, KT, and AHLV contributed to benthic data curation and quality control. HED wrote the paper with input from HLF. All co-authors contributed to editing and revision.

330 *Competing interests.* At least one of the (co-)authors is a member of the editorial board of *Climate of the Past*. The authors have no other competing interests to declare.

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