Global and Planetary Change 232 (2024) 104316

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Pliocene Model Intercomparison Project Phase 3 (PlioMIP3) – Science plan and experimental design

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ARTICLE INFO

Editor: Howard Falcon-Lang

Keywords:
Climate modelling
Palaeoclimate
Pliocene
PlioMIP

ABSTRACT

The Pliocene Model Intercomparison Project (PlioMIP) was initiated in 2008. Over two phases PlioMIP has helped co-ordinate the experimental design and publication strategy of the community, which has included an increasing number of climate models and modelling groups from around the world. It has engaged with palaeoenvironmental scientists to foster new data synthesis supporting the construction of new model boundary conditions, as well as to facilitate new data-model comparisons. The work has advanced our understanding of Pliocene climates and environments, enhanced our knowledge regarding the ability of complex climate and Earth System models to accurately simulate climate change, and helped to refine our estimates of how sensitive the climate system is to forcing conditions.

In this community protocol paper, we outline the scientific plan for PlioMIP Phase 3 (PlioMIP3). This plan provides the required guidance to participating modelling groups from around the world to successfully set up and perform PlioMIP3 climate model experiments. The project is open to new participants from the scientific community (both from the climate modelling and geosciences communities).

In PlioMIP3, we retain the PlioMIP2 Core experiments (Eoi^{400}, E^{280}) and extend the Core requirements to include either an experiment focussed on the Early Pliocene or an alternative Late Pliocene simulation (or both). These additions (a) allow a comparison of Early and Late Pliocene warm intervals and help build research connections and synergy with the MioMIP (Miocene Model Intercomparison Project - also known as DeepMIP-Miocene) and PlioMioVAR projects (Pliocene-Miocene Variability Working Group), and (b) create an alternative time slice simulation for 3.205 Ma (MIS KM5c) through removal of some of the largest palaeogeographic differences introduced between PlioMIP1 and 2 resulting in minimal land-sea mask variations from the modern. In addition, we present ten optional experiments designed to enhance our assessment of climate sensitivity and to explore the uncertainty in greenhouse gas-related forcing. For the first time, we introduce orbital sensitivity experiments into the science plan, as well as simulations incorporating dynamic vegetation-climate feedbacks and an experiment designed to examine the potential significance of East Antarctic Ice Sheet boundary condition uncertainty. These changes enhance palaeo-to-future scientific connections and enable an exploration of the significance of palaeogeographic uncertainties on climate simulations.

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https://doi.org/10.1016/j.gloplacha.2023.104316
Received 8 September 2023; Received in revised form 17 November 2023; Accepted 17 November 2023
Available online 22 November 2023

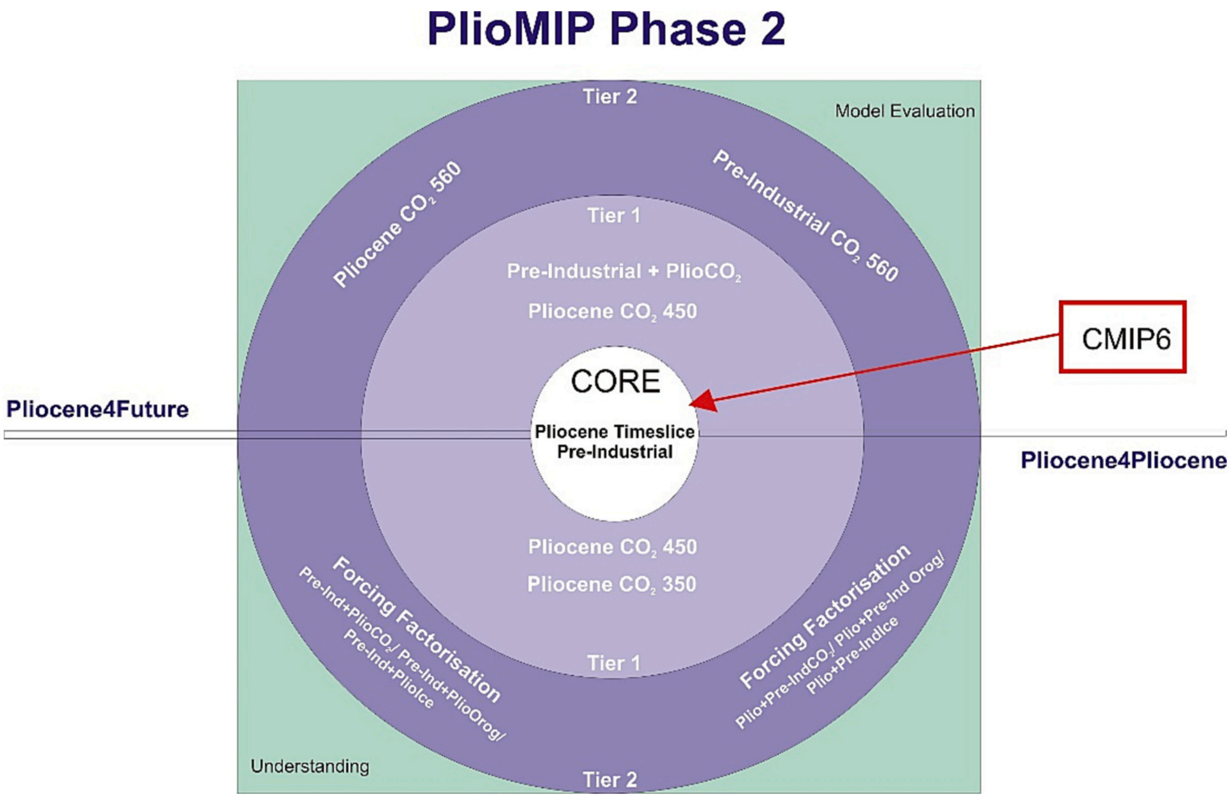

Fig. 1. Experimental design used in PlioMIP2 (redrawn from Haywood et al., 2016).

1. Introduction

The Pliocene Model Intercomparison Project (PlioMIP) was established in 2008. The project facilitates and co-ordinates an international effort to compare multiple climate model simulations for the Pliocene Epoch (Haywood et al., 2010). The project's scientific objectives are to explore and quantify climate model variability and uncertainty, and to understand the sensitivity of the climate system to forcing in the long-term (Haywood et al., 2016). PlioMIP activities to date have occurred in two discrete phases.

PlioMIP Phase 1 (PlioMIP1; 2008-2016) consisted of atmosphere-only and coupled ocean-atmosphere climate model simulations for the mid-Piacenzian Warm Period (mPWP; ~3.3 to 3 Ma, previously referred to as the mid-Pliocene Warm Period; Haywood et al., 2010, 2011). These simulations used the U.S. Geological Survey (USGS) Pliocene Research Interpretation and Synoptic Mapping's third palaeoenvironmental reconstruction (PRISM3D; Dowsett et al., 2010) as required model boundary conditions. PRISM3 marine proxy data (Dowsett et al., 2013) were used to evaluate marine climates, and the Salzmann et al. (2008, 2013) terrestrial proxy data were used to evaluate terrestrial climates. Eight atmosphere-only and eight coupled ocean-atmosphere climate models contributed to PlioMIP1 (e.g., see Haywood et al., 2013a; Dowsett et al., 2013).

PlioMIP Phase 2 (PlioMIP2; 2016-2022; Haywood et al., 2016; Fig. 1) used the PRISM4 palaeoenvironmental reconstruction as boundary conditions (Dowsett et al., 2016). Seventeen climate models participated, running coupled ocean-atmosphere simulations (e.g., see Haywood et al., 2020 which included outputs from sixteen models and Williams et al., 2021 who presented results of the seventeenth model in the PlioMIP2 ensemble – HadGEM3). In PlioMIP2, the temporal focus was enhanced from the 300 ky mPWP time slab to the study of a discrete time slice in the Late Pliocene with a near modern orbital forcing, centred on 3.205 Ma, consistent with the peak Marine Isotope Stage [MIS] KM5c; (Haywood et al., 2013b). This focus on MIS KM5c, (a) provided greater certainty in the specification of appropriate orbital conditions within PlioMIP models, (b) reduced the impact of temporal uncertainty on data-model comparisons, and (c) enhanced PlioMIP activities in addressing questions of maximum relevance for the understanding of future climate change. In addition to the core Pliocene simulation all groups were asked to perform, the PlioMIP2 scientific remit expanded to include several additional simulations addressing both 'Pliocene for Pliocene' (P4P) and 'Pliocene for Future' (P4F) agendas (Fig. 1). These simulations were prioritised across two tiers of activity (Haywood et al., 2016) and included (a) atmospheric CO_2 sensitivity experiments to bracket CO_2 forcing uncertainty, (b) experiments to facilitate using the PlioMIP simulation ensemble to successfully quantify Climate and Earth System Sensitivity, and (c) forcing factorization simulations enabling individual contributions of Pliocene boundary conditions to the overall signal of climate change to be determined. Evaluation of model data for the oceans was accomplished through reference to the geological ground truthing syntheses of Foley and Dowsett (2019) and McClymont et al. (2020). Evaluation of model performance over the land was performed using proxy data derived from the Salzmann et al. (2013) and Feng et al. (2022) compilations.

Both PlioMIP1 and 2 made valuable contributions to the Intergovernmental Panel on Climate Change (IPCC) 5th and 6th Assessment Reports (AR5 and AR6) and supported a dedicated cross-chapter box on the Pliocene in the IPCC Working Group I (WGI) contribution to AR6 (IPCC, 2013; IPCC, 2021). The Pliocene control simulation from PlioMIP2 (Eoi400) was a formally recognised experiment within the Coupled Model Intercomparison Project Phase 6 (CMIP6).

PlioMIP integrates the data and modelling communities, attracting involvement through proposing an exciting science plan, weighing scientific ambition against feasibility, ensuring that the scientific benefits outweigh the scientific investment, and facilitating data-model comparison and model evaluation.

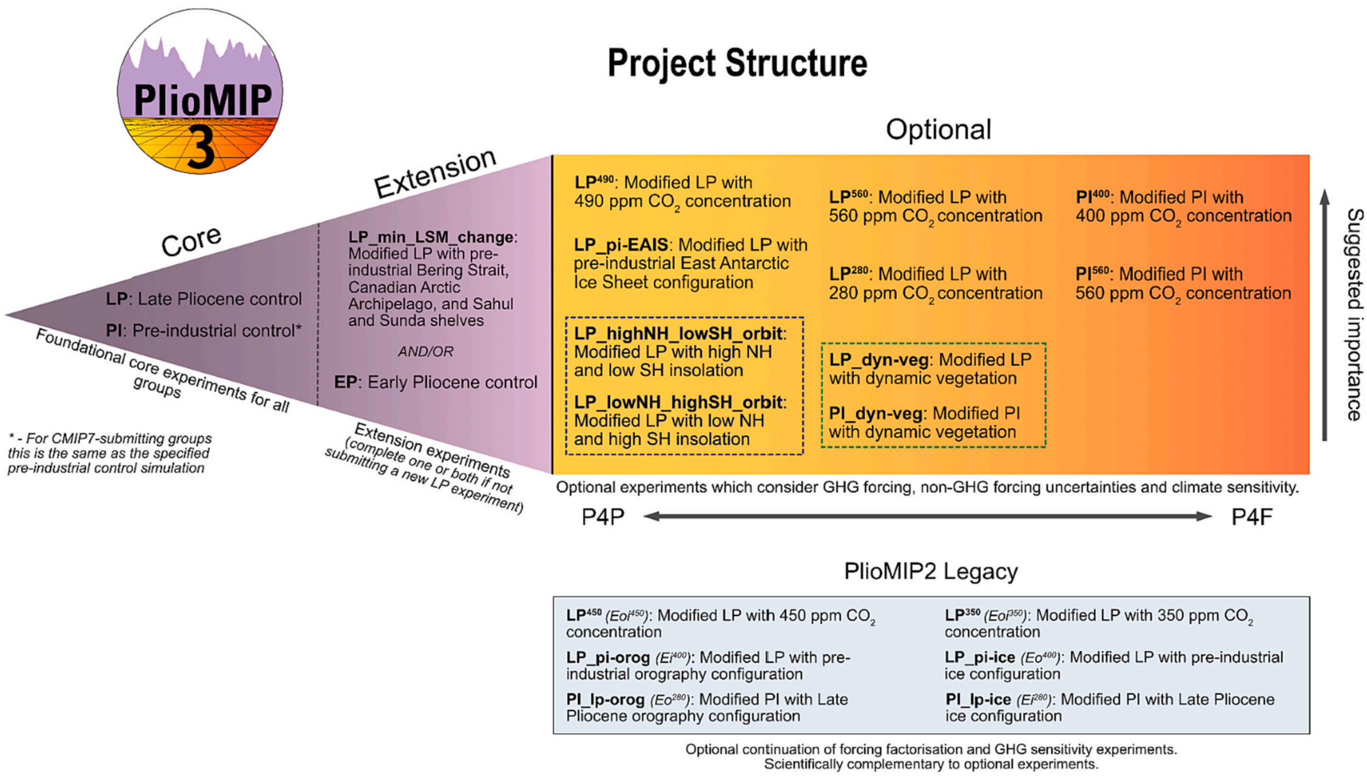

Fig. 2. Proposed programme of work for PlioMIP3. Core experiments must be performed by all participating groups. Groups are encouraged to perform at least 1 additional experiment from the Extension section, and this is a mandatory requirement if you are not submitting a new Core Late Pliocene (*LP*) experiment. Participants may choose to perform any experiments from the Optional section, noting that some experiments have the highest utility when performed in concert with another experiment (those relationships are highlighted by the coloured dashed boxes). Experiments in the Optional section are also arranged to highlight those most relevant for 'Pliocene for Pliocene' (P4P) and 'Pliocene for Future' (P4F) agendas.

2. The PlioMIP3 science plan – what is new and what has been retained?

In its maturity, PlioMIP now operates in the context of several model intercomparison projects and community efforts occurring across palaeoclimatology (e.g., MioMIP and PlioMioVAR). Therefore, PlioMIP3 seeks to maximise the scientific benefits that can be achieved through both new elements and those retained from PlioMIP2 (Fig. 2; Table 1). This paper outlines the overall scientific strategy and framework for PlioMIP3 and clarifies technical aspects of performing the simulations.

2.1. Experiment nomenclature

In PlioMIP2, a nomenclature was introduced to simplify the description of experiments for climate modellers. This nomenclature was Ex^c, where *c* was the concentration of atmospheric CO_2 in ppm, and *x* were any boundary conditions that were Pliocene as opposed to pre-industrial (where *x* was any or none of *o* and/or *i*, and where *o* was orography and *i* was ice sheets). Note that in all PlioMIP2 simulations, orography, lakes, and soils were modified in unison, and so *o* denoted changes to orography, bathymetry, land–sea mask, lakes and soils combined. Note that at the time of devising the nomenclature, it was anticipated that all groups would run with dynamic interactive vegetation. In reality, all but one group ran with prescribed vegetation, and so Eoi^{400} could more accurately be described as $Eoiv^{400}$.

Whilst this notation proved to be an effective shorthand for the climate modelling community, it proved to be less accessible to the wider user base of PlioMIP outputs. In addition, the nomenclature relied on there being only two classifications of experiment (Pliocene and pre-industrial). In PlioMIP3, this dual classification system is no longer valid due to the addition of an Early Pliocene experiment.

For PlioMIP3 we propose the adoption of a nomenclature which is more easily accessible to non-climate modelling communities, and which can accommodate the temporal expansion of the experimental design to include the Early Pliocene. This classification is based around the time periods *PI, LP* and *EP* (the pre-industrial, Late Pliocene, and Early Pliocene respectively). In this system the three basic categories reflect a package of boundary conditions which are specific to the time period (see Table 1). Superscripted values after the time period classification (e.g., PI^{400}) represent a specific modification of the atmospheric CO_2 concentration. Information beyond the time period classification also details changes to the experiments descriptively (e.g., *LP_pi-EAIS* denotes a *LP* experiment modified with a pre-industrial East Antarctic Ice Sheet).

2.2. Core experiments (compulsory; PI and LP)

Two experiments comprise the Core of PlioMIP3, a Late Pliocene simulation (*LP*) and a pre-industrial simulation (*PI*). The *LP* experiment (3.205 Ma, consistent with the peak of MIS KM5c) is the same as the Core Pliocene simulation within PlioMIP2 (Eoi^{400}) using the PRISM4/PlioMIP2 enhanced boundary conditions data set (see Haywood et al., 2016; Dowsett et al., 2022). The PlioMIP2 Eoi^{400} simulation provided demonstrable improvements in specific aspects of regional data-model comparison compared to the control Pliocene simulation in PlioMIP1 (e.g., in North Atlantic and Nordic Sea sea-surface temperatures (SSTs), and in Australian precipitation; Haywood et al., 2020). In addition, retaining this experiment in PlioMIP3 provides a continuity that is useful for the assessment of newer versus older generations of climate models, which has considerable value in the context of IPCC assessments. These experiments are the foundation of all comparisons between Pliocene climate states and the pre-industrial climate state.

Table 1
List of proposed experiments within PlioMIP3. Short identification names (ID), short descriptions and key boundary condition information are provided. Experiments are grouped into: Core (compulsory experiments); Extension (it is recommended to complete one or both, and completing at least one Extension experiment is compulsory if a group is not submitting a new Pliocene Core experiment); Optional (choose based on specific interest); PlioMIP2 Legacy (optional). *If you are a CMIP7 submitting group, use the CMIP7 set value used for the pre-industrial control run. See PI experiment sheet (Annex 1). $^{\Psi}$Note that there are small variations in the land-sea mask in this experiment around East Antarctica to accommodate the specified pre-industrial EAIS.

PlioMIP 3 ID (*PlioMIP2 ID if appropriate*)	Description	LSM	Topography (incl. soils/lakes)	Vegetation	Ice	CO_2 (ppm)	Orbit*	Tier
PI (*E^{280}*)	Pre-industrial control experiment	PI	PI	PI	PI	280*	PI	Core
LP (*Eoi^{400}*)	Late Pliocene control experiment	LP	LP	LP	LP	400	PI	Core
LP_min_LSM_change	Late Pliocene with pre-industrial Bering Strait, Canadian Arctic Archipelago, Sunda/Sahul shelves	Alternate LP	Alternate LP	Alternate LP	LP	400	PI	Extension
EP	Early Pliocene control experiment	LP+open CAS	LP+open CAS	LP+open CAS	LP	490	PI	Extension
LP_highNH_lowSH_orbit	Late Pliocene experiment with high NH summer and low SH summer insolation	LP	LP	LP	LP	400	3.037 Ma	Optional
LP_lowNH_highSH_orbit	Late Pliocene experiment with low NH summer and high SH summer insolation	LP	LP	LP	LP	400	3.049 Ma	Optional
LP^{490}	Late Pliocene experiment with 490 ppm CO_2 concentration	LP	LP	LP	LP	490	PI	Optional
LP_pi-EAIS	Late Pliocene experiment with a pre-industrial East Antarctic Ice Sheet (EAIS)	LP + PI EAIS $^{\Psi}$				400	PI	Optional
LP_dyn-veg	Late Pliocene experiment with dynamic vegetation	LP	LP	Dynamic	LP	400	PI	Optional
PI_dyn-veg	Pre-industrial experiment with dynamic vegetation	PI	PI	Dynamic	PI	280*	PI	Optional
LP^{280} (*Eoi^{280}*)	Late Pliocene experiment with 280 ppm CO_2 concentration	LP	LP	LP	LP	280*	PI	Optional
LP^{560} (*Eoi^{560}*)	Late Pliocene experiment with 560 ppm CO_2 concentration	LP	LP	LP	LP	560	PI	Optional
PI^{400} (*E^{400}*)	Pre-industrial experiment with 400 ppm CO_2 concentration	PI	PI	PI	PI	400	PI	Optional
PI^{560} (*E^{560}*)	Pre-industrial experiment with 560 ppm CO_2 concentration	PI	PI	PI	PI	560	PI	Optional
LP^{350} (*Eoi^{350}*)	Late Pliocene experiment with 350 ppm CO_2 concentration	See Haywood et al. (2016) and Lunt et al. (2021).					PI	PlioMIP2 legacy
LP^{450} (*Eoi^{450}*)	Late Pliocene experiment with 450 ppm CO_2 concentration						PI	PlioMIP2 legacy
LP_pi-ice (*Eo^{400}*)	Late Pliocene experiment with pre-industrial ice						PI	PlioMIP2 legacy
LP_pi-orog (*Ei^{400}*)	Late Pliocene experiment with pre-industrial orography (outside of ice sheet regions)						PI	PlioMIP2 legacy
PI_lp-ice (*Ei^{280}*)	Pre-industrial experiment with Late Pliocene ice						PI	PlioMIP2 legacy
PI_lp-orog (*Eo^{280}*)	Pre-industrial experiment with Late Pliocene orography (outside of ice sheet regions)						PI	PlioMIP2 legacy

2.3. Extension experiments (compulsory/voluntary)

Two experiments designed to extend and enhance the Core experiments have been added. It is compulsory to submit at least one extension experiment unless the modelling group is submitting a new *LP* experiment (i.e., a new PlioMIP2 *Eoi^{400}* experiment using the PRISM4 enhanced boundary conditions). All groups are encouraged to complete both Extension experiments if possible.

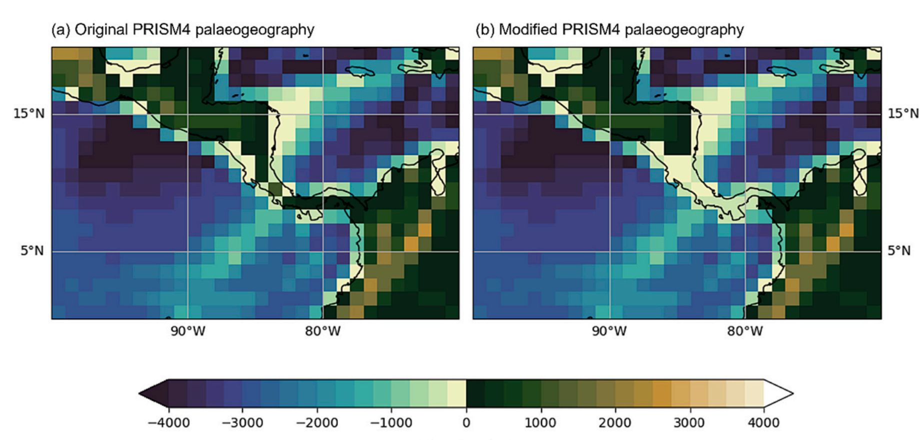

Fig. 3. (a) Original PRISM4 palaeogeography used in the *LP* experiment and (b) palaeogeography of the open Central American Seaway (CAS) to be used in the *EP* experiment.

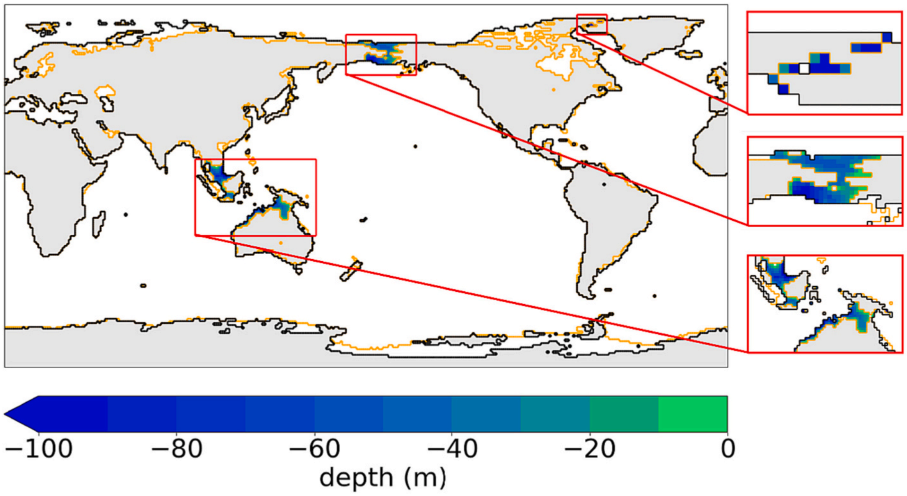

Fig. 4. Map showing *LP* and PI LSM (black and orange outlines respectively) with grey shading showing regions that are land in both the *LP* and the PI. Zoomed boxes show the geographical regions which are ocean in the *LP_min_LSM_change* (and modern) but land in the *LP*, with colours denoting the depth of the bathymetry in these regions. Note that because this boundary condition will be applied as an anomaly (see section 2.6) these gateways will match each model's local preindustrial simulation.

2.3.1. Early Pliocene experiment (EP)

In response to increased palaeoclimate community interest in Early Pliocene climate and environments, PlioMIP3 expands the temporal focus of its activities to include a simulation incorporating two key differentiating features of the Early Pliocene (experiment *EP*). This expansion enables a comparison of model results for the Late and Early Pliocene in a coordinated way. It also enables PlioMIP to construct part of a scientific bridge to the Miocene. This epoch is being studied by the Miocene Model Intercomparison Project (MioMIP; Burls et al., 2021) and the PAGES-supported PlioMioVAR project. PlioMIP3 will connect with MioMIP, facilitating the intercomparison of model results over multiple geological time periods.

The *EP* experiment needs a change in model boundary conditions capable of generating a clear climate change signal between the Early and Late Pliocene. Therefore, the PlioMIP3 *EP* experiment has an open Central American Seaway which must be wide enough to allow effective water mass exchange between the Atlantic and Pacific Oceans (Fig. 3). The depth of the open Central American Seaway was determined based on the unedited digital elevation model (DEM) used in PlioMIP2. Grid boxes that are land in the *LP* experiment (Fig. 3a), but ocean in the *EP* experiment (Fig. 3b) are assigned a depth of 250m if they are 83°W - 85°W, and a depth of 500m if they are 79°W-83°W. These depths allow internal consistency between the *EP* experiment and the original DEM. This aspect of the *EP* experiment is supported in the published literature, which generally characterises the Central American Seaway as open in the Early Pliocene, and closed in the Late Pliocene (Keigwin, 1982; Cronin and Dowsett, 1996; Burton et al., 1997; Haug and Tiedemann, 1998; Bell et al., 2015; O'Dea et al., 2016; Dowsett et al., 2019). Even so, the degree to which this seaway was partially open, and to what degree it allowed effective flow between the Pacific and Atlantic, remains a matter of debate.

In addition, we increase CO_2 from 400 ppm in the *LP* experiment to 490 ppm in the *EP* experiment (further reasoning for this exact change is provided in section 2.4.1). Whilst the mean difference in atmospheric CO_2 concentrations between the Early and Late Pliocene warm intervals remains ambiguous, palaeoenvironmental data suggest that the Early Pliocene was warmer than the Late Pliocene (e.g., Fedorov et al., 2013) and in theory this could be related to a higher mean CO_2 atmospheric concentration (e.g., as suggested by the alkenone-based CO_2 estimates of Zhang et al., 2013). All other conditions for the *EP* experiment will remain consistent with the *LP* experiment (i.e. *Eoi*^{400} in PlioMIP2). We have identified two Early Pliocene target time slices (PRISM5.1 and PRISM5.2) for verification data synthesis and data-model comparison (see section 3.2; Dowsett et al., 2023).

2.3.2. Alternative Late Pliocene experiment (LP_min_LSM_change)

The PlioMIP2 *Eoi*^{400} experiment utilised the PRISM4 palaeogeographic reconstruction. It incorporated a full dynamic topography and glacial isostatic adjustment (GIA) method (Dowsett et al., 2016). The result was an internally consistent and fully reproducible topographic and land-sea mask (LSM) reconstruction. Emergent properties of the reconstruction included a closed Canadian Arctic Archipelago, a closed Bering Strait and subaerial Sahul and Sunda Shelves. These changes led to better agreement between climate simulations and proxy data in some regions but not others. For example, in several models, the PlioMIP1 signal of enhanced precipitation over western North America (Ibarra et al., 2018; Menemenlis et al., 2021; White et al., 2022) is weak or absent in PlioMIP2. This is a feature potentially at odds with Late Pliocene age leaf wax δD records (Bhattacharya et al., 2022) and lake level records from the region (Pound et al., 2014).

The alternate Late Pliocene time slice experiment, *LP_min_LSM_change*, for 3.205 Ma is identical to the *LP* experiment except that it uses each modelling group's pre-industrial palaeogeography in the Canadian Arctic Archipelago, Bering Strait, and Sahul and Sunda Shelf regions (Fig. 4). In this experiment the Bering Strait will be open, the Sahul and Sunda shelves submerged, and the Canadian Arctic Archipelago could be either open or closed depending on the model's characterisation of this region in the pre-industrial. This experiment enables us to determine the regional impacts of these geographic features the evolution of which are only partially constrained geologically (e.g., Matthiessen et al., 2009), yet have the potential to significantly impact climate model simulations (e.g., Otto-Bliesner et al., 2017), and to analyse the western North America precipitation question in greater detail.

2.4. Optional experiments

PlioMIP3 includes ten optional experiments (Table 1, Fig. 2). These experiments sample uncertainties in GHG and non-GHG boundary conditions, enable us to better understand the influence of specific forcings on the Pliocene climate, and inform future work on climate sensitivity. Seven of these experiments are simple variations of either the *LP* or *PI* experiments with CO_2 variations or orbital forcing sensitivity tests. Fig. 2 indicates approximately where these experiments fall in the 'Pliocene for Pliocene' (P4P) or 'Pliocene for Future' (P4F) agendas as

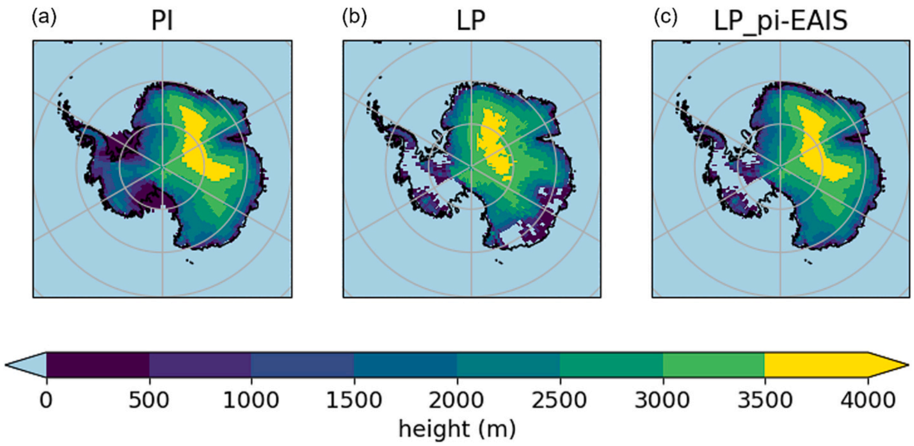

Fig. 5. Height (m) above sea level for experiments PI, LP and LP_pi-EAIS.

well as our assessment of the overall scientific priority of the suite of Optional experiments (although we recognise that this is subjective and that scientific priorities may vary between groups).

2.4.1. Experiments LP^{280}, LP^{490} and LP^{560}

These experiments explore GHG forcing uncertainty in the context of simulating the Late Pliocene time slice (3.205 Ma). They are also useful in the context of climate sensitivity assessments, and in the case of LP^{560} simplifies the computation of ECS. The specific choice for LP^{490} was inspired by the Hopcroft et al. (2020) non-CO_2 GHG study, which determined an upper range on non-CO_2 GHG radiative forcing of Late Pliocene climate of an additional 1.1 Wm^{-2}. This radiative forcing level approximately equates to a total CO_2-based forcing of 490 ppm rather than 400 ppm and informed our choice of 490 ppm for the EP experiment. Thus, the LP^{490} and *EP* simulations can be compared directly, providing the ability to determine the impact of the Central American Seaway change in isolation of CO_2 forcing.

2.4.2. Experiments PI^{400} and PI^{560}

Experiments PI^{400} and PI^{560} are companions of *LP* and LP^{560}, improving our understanding of how much GHG forcing, relative to other Pliocene boundary conditions, influences the regional pattern of climate change (Burton et al., 2023). These experiments are also relevant to climate sensitivity assessments.

2.4.3. Experiment LP_pi-EAIS

Experiment *LP_pi-EAIS* addresses known uncertainties in Pliocene ice sheet reconstructions. PRISM4 ice volume and sea-level estimates fall near the upper end of the IPCC AR6 uncertainty range for Pliocene sea level (+5 to +25 m). Assigning a modern volume to the Late Pliocene East Antarctic Ice Sheet (EAIS) enables the production of an *LP* experiment with an ice volume equivalent to the central estimate of IPCC AR6 reported Pliocene sea level. It will also lead to the production of climate simulations that can usefully inform a second phase of the Pliocene Ice Sheet Modelling Intercomparison Project (PLISMIP; Dolan et al., 2018). Previous studies have shown that the climate forcing used in ice sheet model experiments can be more important than uncertainties derived from structural differences and the uncertainty in ice sheet models themselves (e.g., Dolan et al., 2018). Topographic details over Antarctica are shown for the various model geographies in Fig. 5.

2.4.4. Experiments LP_highNH_lowSH_orbit and LP_lowNH_highSH_orbit

Experiments *LP_highNH_lowSH_orbit* and *LP_lowNH_highSH_orbit* are a pair of orbital forcing sensitivity tests to be completed together. Pliocene proxy records show evidence for climate variability over orbital timescales. Exploring how orbital forcing can influence regional and seasonal patterns of Pliocene climate will support a wealth of combined data-model studies. These experiments represent actual time slices within the Late Pliocene (Table 1; Annex 1) that have enhanced seasonal differences in hemispheric insolation, compared to the *LP* experiment, which uses a modern orbital configuration (see Annex 2 and Figure A1 for more details). High Northern Hemisphere summer insolation with low Southern Hemisphere summer insolation is represented by the *LP_highNH_lowSH_orbit* experiment, and low Northern Hemisphere summer insolation with high Southern Hemisphere summer insolation is represented by the *LP_lowNH_highSH_orbit* experiment. The values for the orbital parameters for these two experiments are fully described on the relevant experiment sheet provided in Annex 1. Please see Annex 3 for more details on calendar correction requirements for the Late Pliocene orbital sensitivity tests.

2.4.5. Experiments LP_dyn-veg and PI_dyn-veg

Experiments *LP_dyn-veg* and *PI_dyn-veg* (to be completed as a pair) will enable PlioMIP3 to explore, in a coordinated way, the importance of including dynamic vegetation climate feedbacks for the first time. Most PlioMIP simulations have been performed using prescribed vegetation. Limitations in the ability to date and correlate terrestrial geological successions means, however, that the prescribed vegetation used in PlioMIP2 (Salzmann et al., 2008, 2013), and used again in PlioMIP3, is based on a data compilation that spans >1 My. The degree to which this is consistent with other time specific boundary conditions and forcings (e.g., GHG, orbit etc.) remains uncertain.

2.5. PlioMIP2 legacy experiments (voluntary)

As part of PlioMIP2, forcing factorization experiments were proposed to assess the relative importance of various boundary condition changes contributing to Pliocene warmth (Haywood et al., 2016; and see corrections to the forcing factorisation given in Lunt et al., 2021). Some or all of these experiments were performed by a small number of PlioMIP2 modelling groups and have proven to be valuable for several different scientific applications. These include understanding the importance of different forcing and boundary condition changes on the pattern of regional climate change (Feng et al., 2022), as well as informing combined model-data studies (e.g., Chandan and Peltier, 2018; Burton et al., 2023). Therefore, PlioMIP3 retains the option for groups to complete these experiments at their discretion (experiments *LP_pi-ice* (Eo^{400} in PlioMIP2), *LP_pi-orog* (Ei^{400} in PlioMIP2), *PI_lp-orog* (Eo^{280} in PlioMIP2) and *PI_LP-ice* (Ei^{280} in PlioMIP2). Given their ease of execution, PlioMIP3 also retains the option to perform two additional *LP* sensitivity experiments with atmospheric CO_2 values of 350 ppm (LP^{350}; Eoi^{350} in PlioMIP2) and 450 ppm (LP^{450}; Eoi^{450} in PlioMIP2), to enhance abilities to assess the uncertainty in Pliocene climate prediction relating to ambient CO_2 concentration.

2.6. Boundary condition implementation, model initialisation, spin-up and integration

To maintain scientific continuity with PlioMIP2, which is important given the retention of the PlioMIP2 Eoi^{400} experiment as the Core Late Pliocene experiment in PlioMIP3 (*LP*), our general approach towards boundary condition implementation, model initialisation, spin-up and integration length remains the same as that recommended in PlioMIP2 (see Haywood et al., 2016). Boundary condition files for PlioMIP3 Core, Extension and Optional experiments have been published (Haywood et al., 2023) and are available online (https://www.sciencebase.gov/catalog/item/64df7f1fd34e5f6cd553baa1).

In the same way as PlioMIP2, to ensure that the climate anomalies (palaeo minus present day) from all PlioMIP3 models are directly comparable, i.e., that they reflect differences in the models themselves rather than the differences of modern boundary conditions, Pliocene topography (and bathymetry) should be implemented as an anomaly to whatever modern topographic data set is used by each modelling group in their own model. To create the Pliocene topography (and bathymetry) the difference between the PRISM4 Pliocene and PRISM4 Modern topography (bathymetry) should be calculated and added to the local modern topographic (bathymetric) data sets each participating modelling group employs within their own pre-industrial control simulations, ($Local^{ModernTOPO}$ or $Local^{ModernBATH}$), such that:

$$Plio^{TOPO} = PRISM4^{PlioTOPO} - PRISM4^{ModernTOPO} + Local^{ModernTOPO}$$

and

$$Plio^{BATH} = PRISM4^{PlioBATH} - PRISM4^{ModernBATH} + Local^{ModernBATH}$$

With this formulation it is possible that on occasion grid cells may become land where the intention is for an ocean cell to be specified and vice versa. In this case the specified Pliocene LSM takes precedence. In other words, this ensures that the integrity of Pliocene LSM boundary condition data is always preserved.

The only exception to using the anomaly method (above) to calculate topography and bathymetry is in the opening of the Central American Seaway in the *EP* experiment. In this experiment the intention is that the Central American Seaway gateway is deep enough and wide enough for effective water mass exchange between the Atlantic and Pacific. It is also the intention that the gateway is of a similar depth and width between models to allow for maximum inter-model comparability. Therefore, the Central American Seaway opening should be based on the absolute bathymetry values provided, unless there is a scientific or technical reason why an alternative method for opening the Central American Seaway should be used. However, such procedures should be documented by participating modelling groups.

For all PlioMIP3 experiments the integration length is at least 500 simulated years in accordance with CMIP (Coupled Model Intercomparison Project) general guidelines for equilibrated coupled model experiments (Taylor et al., 2012). Whilst 500 simulated years is unlikely to be sufficient to bring the climate system to equilibrium (Eyring et al., 2016), the challenge of doing so with recently developed full complexity Earth System Models is recognised and fully appreciated. However, participating groups should make every reasonable effort to ensure their simulations are as close to equilibrium as possible. Documenting the experiment spin-up history and providing timeseries of key climate variables such as global annual mean temperature and integrated ocean temperature and salinity, as well as calculations of the imbalance in the energy budget at the top of the atmosphere (ToA; Wm^{-2}) is a useful way to help guide the use and interpretation of individual model data.

Experiment *PI* should be initialised from an already spun-up or partially spun-up pre-industrial simulation, or in a way which conforms to an initial condition recommended by CMIP. All Pliocene experiments (e.g., *LP*, *EP*) in the Core, Extension, Optional, and PlioMIP2 legacy experiments should preferably be initialised from a pre-existing Pliocene simulation (e.g., starting from the end of the PlioMIP2 Eoi^{400} simulation). If this is not available, they should be initialised from a simulation using a pre-industrial condition. Experiments with the notation starting *PI* in the Optional and PlioMIP2 legacy experiment list should be initialised in the same way as the Core *PI* experiment. Groups should ensure that their initialisation of Pliocene and pre-industrial-based experiments is internally consistent across Core, Extension, Optional, and PlioMIP2 legacy experiments. Full details of boundary conditions and initial states are included in Annex 1.

To enhance the connection to proxy-based data sets, we encourage the use of stable water isotope-enabled models. We envision simulated stable isotope data being used in concert with proxy methods to improve understanding of freshwater inputs, temperature, ocean chemistry, and water mass circulation. If a model has this ability, and sufficient computational resources are available, initialising the stable water isotope model fields from an existing isotope enabled LP simulation, or if this is unavailable, from a pre-industrial condition is recommended.

2.7. Variables, output format, data processing, storage, deadlines, and data embargo

If a PlioMIP3 Core experiment is adopted as a CMIP7 simulation, model data for this experiment must use the Climate Model Output Rewriter (CMOR) format and be stored on an ESGF (Earth System Grid Federation) node. The CMOR library has been specially developed to help meet the requirements of the model intercomparison, therefore its use is recommended if possible. Further details of CMIP(7) experiments and required outputs/CMOR file formats will be made available on the CMIP(7) website in due course. For non CMIP(7) submitting groups performing PlioMIP3 experiments, the list of required variables can be found on the PlioMIP Phase 3 website (https://www.sciencebase.gov/catalog/item/648c8514d34ef77fcaff3eab?community=Pliocene+Model+Intercomparison+Project%2C+Phase+3). All model outputs will be deposited at the University of Leeds, UKusing the Globus data transfer service (https://it.leeds.ac.uk/it?id=kb_article&sysparm_article=KB0015444). Requests for access should be directed to the corresponding author of this paper. Data submitted using the Globus data transfer service will be subject to a public embargo for 12 months following the submission of the last anticipated model data to the repository. This is to ensure that groups contributing model data to PlioMIP3 can lead the preparation of a scientific study/publication in their area(s) of specific interest. The final deadline for submission is anticipated to be March 31st, 2025. The data embargo period is therefore anticipated to run until March 31st, 2026.

PlioMIP3 request participants to prepare their data files to meet the following constraints (regardless of the way their models produce and store their results).

- Data files must be in the (now widely used) netCDF binary file format and conform to the CF (Climate and Forecast) metadata convention (outlined on the website http://cf-pcmdi.llnl.gov).
- There must be only one output variable per file.
- For the data that are a function of longitude and latitude, only regular grids (grids representable as a Cartesian product of longitude and latitude axes) are allowed.
- Converting variables from hybrid to pressure coordinates can be problematic for users, therefore we recommend uploading variables in pressure coordinate as well as hybrid coordinate formats.
- To allow for diagnosing internal variability of a simulation providing model outputs as a time series of at least 100 years is recommended.

3. Consideration of proxy data-model synergies/requirements

The PlioMIP project has maintained strong links with the palaeo-data community through a long-standing union with the US Geological Survey PRISM project (Dowsett et al., 2010; 2012; 2013a, b; 2016, Dowsett et al., 2019; Foley and Dowsett, 2019; Dowsett et al., 2023), as well as

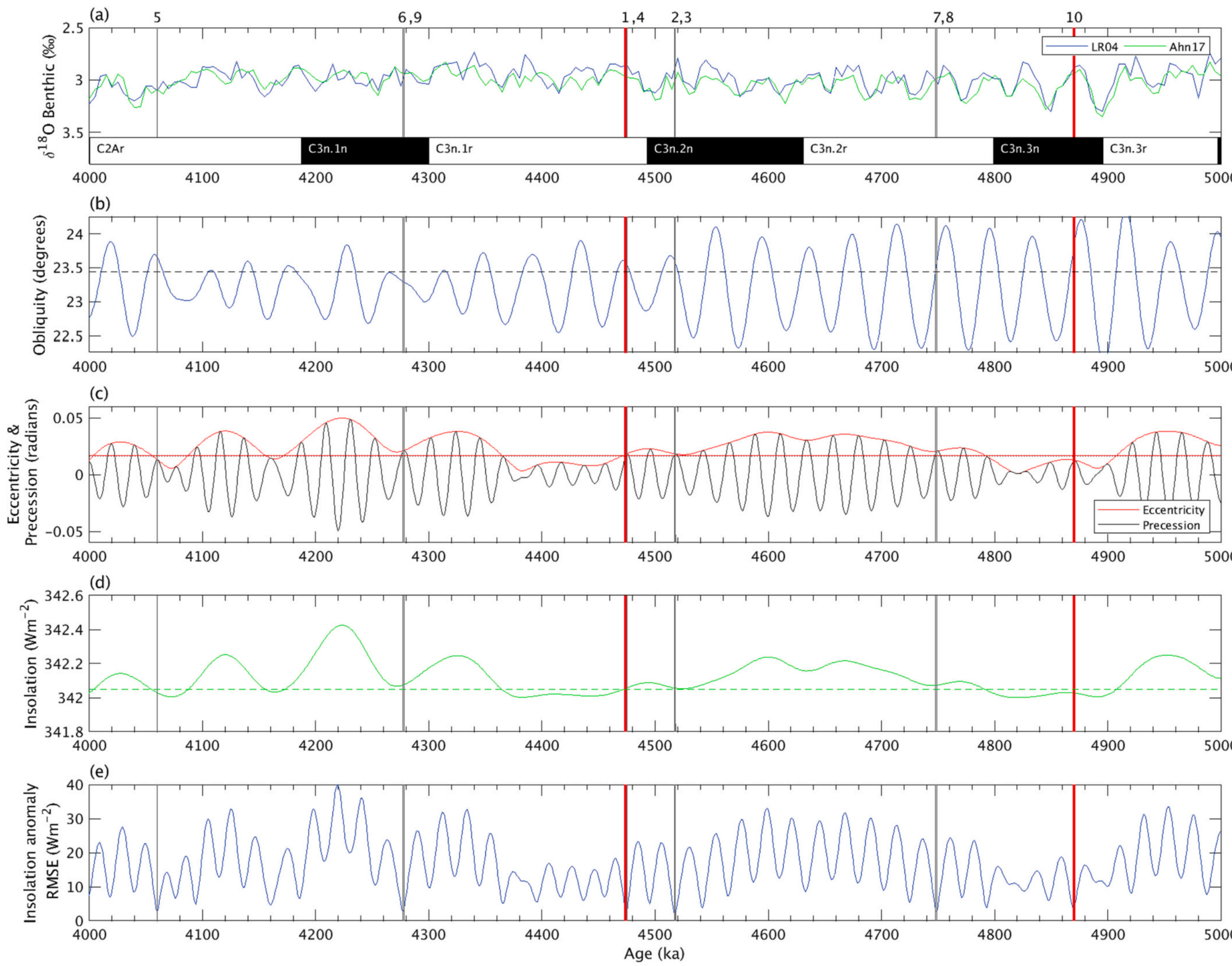

Fig. 6. (a) Lisiecki and Raymo (2005, blue line) and Ahn et al. (2017, green line) benthic oxygen isotope stack. The record of magnetic reversals of Gradstein et al. (2020) is also shown. (b) obliquity, with dashed horizontal line showing the present-day value (23.4 degrees); (c) precession (black line) and eccentricity (red line) plotted on same axis as derived from the astronomical solution of Laskar et al. (2004) (La04), with horizontal solid red line showing present-day values for eccentricity (0.0167) and precession (0.01628 radians); (d) the variation in global mean Top of the Atmosphere (TOA) insolation (Wm^{-2}) according to La04 with the horizontal dashed green line denoting the modern value of global mean insolation (342.05 Wm^{-2}), and (e) the insolation anomaly calculated as the root mean squared error against the modern TOA insolation. Vertical solid black lines through each of the five panels represent the best-fitting time slice solutions considered in the study and the identified Early Pliocene time slices are shown as solid red vertical lines.

the more recent PlioVAR community effort (McClymont et al., 2020). PlioMIP3 seeks to deepen and widen engagement with the data community and to encourage incorporation of the widest possible array of geological evidence (e.g., temperature, salinity, precipitation, productivity, oxygen saturation, biodiversity gradients, etc.) relevant to the PlioMIP climate model experiments.

3.1. Late Pliocene

PlioMIP2 narrowed the temporal focus of Pliocene experiments. This led to SST syntheses targeting 3.205 Ma (MIS KM5c) developed by the PRISM and PlioVAR projects (Dowsett et al., 2019; Foley and Dowsett, 2019; McClymont et al., 2020). The temporal focus of the Core *LP* experiment has not changed in PlioMIP3 compared to PlioMIP2. Therefore, these datasets remain valid for use with model outputs produced as part of PlioMIP3. It would be valuable, however, considering more recently published SST estimates and re-evaluations of existing SST records, for these datasets to be modified and expanded within the timeframe of PlioMIP3. Point-based data-model comparisons are valuable but can be misleading due to spatial variability between proxy data sites and model simulations. It would be more valuable to consider reconstructed versus simulated variations in key meridional and zonal gradients, and more nuanced and holistic palaeoenvironmental reconstructions are encouraged (Dowsett et al., 2013).

3.2. Early Pliocene

To help support geological data community efforts in engaging with PlioMIP3, with its expanded temporal focus now including the Early Pliocene, we have repeated the analysis used to identify the Late Pliocene time slice (3.205 Ma; Haywood et al., 2013b) for the Early Pliocene (Fig. 6). Based on the astronomical solution of Laskar et al. (2004), we use the annual insolation pattern at the top of the atmosphere to determine time slices in the Early Pliocene that have orbital configurations that are most similar to modern. After considering optimal solutions between 3.6 and 5.322 Ma alongside the Lisiecki and Raymo (2005) and Ahn et al. (2017) benthic oxygen isotope records, as well as the record of geomagnetic reversals (Gradstein et al., 2020), two time

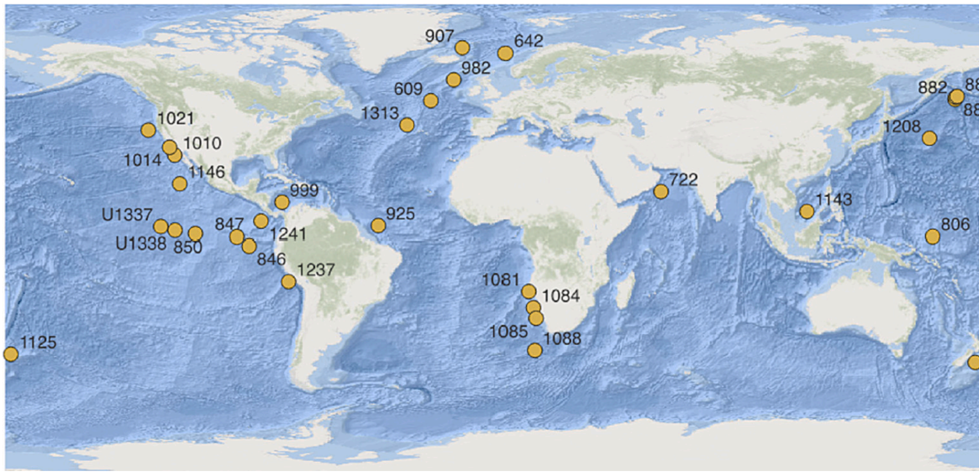

Fig. 7. Sites containing Early Pliocene marine records being investigated by the USGS PRISM group to generate time slice proxy data for model evaluation in PlioMIP Phase 3.

slices corresponding with negative isotope excursions close to magnetic reversals were identified as targets for proxy data collection to compare to the *EP* simulation (see Dowsett et al., 2023; Foley and Dowsett, 2023). These time slices are 4.474 and 4.870 Ma (Fig. 6; Annex 2).

Two Early Pliocene targets were selected due to the uncertainty regarding when the Central American Seaway was most open. The development of a marine palaeoenvironmental reconstruction from each target will help to resolve this uncertainty and to identify which time slice PlioMIP3 better represents. Fig. 7 indicates the distribution of sites with records potentially covering these two Early Pliocene time slices.

To support terrestrial data-model comparison new compilations are planned. These will include a diverse range of proxies, hydrological and temperature variables, and both qualitative and quantitative reconstructions, as well as isotopic data, with links to the full data synthesis housed at WDS-Paleo (https://www.ncei.noaa.gov/products/paleoclimatology). It will also incorporate the very latest re-evaluations of geological age to re-classify our terrestrial geological information to either the Early or Late Pliocene (or Miocene, as the larger Neogene Terrestrial Climate project will also support MioMIP).

4. Conclusion

The experimental design outlined for PlioMIP3 builds upon the successes of PlioMIP2 and provides new opportunities to explore the sensitivity of model results to boundary condition and forcing uncertainties. It provides a means to compare the climate simulations for the Late and Early Pliocene, and an opportunity to link climate studies for the Pliocene and Miocene more coherently. Moving ahead, project participants will consider the publication strategy, including the opportunities around the creation of a dedicated PlioMIP3 special issue to showcase project outcomes. Co-ordinated special issues have provided an opportunity to produce detailed studies of individual model outputs, before moving on to model intercomparison studies. This approach has proven useful to describe model specific differences that need to be understood in order to interpret the model ensemble as a whole.

CRediT authorship contribution statement

A.M. Haywood: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **J.C Tindall:** Conceptualization, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review and editing. **L.E. Burton:** Conceptualization, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review and editing. **M.A. Chandler:** Investigation, Writing - original draft, Writing - review and editing. **A.M. Dolan:** Conceptualization, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review and editing. **H.J. Dowsett:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **R. Feng:** Writing – original draft, Writing – review & editing. **T.L. Fletcher:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **K.M. Foley:** Investigation, Writing – original draft, Writing – review & editing. **D.J. Hill:** Conceptualization, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review and editing. **S.J. Hunter:** Conceptualization, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review and editing. **B.L. Otto-Bliesner:** Investigation, Writing - original draft, Writing - review and editing. **D.J. Lunt:** Investigation, Writing - original draft, Writing - review and editing. **M.M. Robinson:** Investigation, Writing - original draft, Writing - review and editing.**U. Salzmann:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

The authors would like to thank Ayako Abe-Ouchi, Daniel Lunt, and Christian Stepanek for providing initial feedback on the PlioMIP3 science plan. Discussions on this manuscript were facilitated at the 10th EGU Galileo Conference: The warm Pliocene: Bridging the geological data and modelling communities, sponsored by EGU, NERC IODP and PAGES. Discussions were also facilitated by the US Geological Survey during the March 2023 Black Bear Workshop. LEB acknowledges that this work was supported by the Leeds-York-Hull Natural Environment Research Council (NERC) Doctoral Training Partnership (DTP) Panorama under grant no. NE/S007458/1. TLF acknowledges that this project has received funding from the European Union’s Horizon2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101017833. HJD, MMR and KMF acknowledge support from the U.S. Geological Survey Climate R&D Program. RF acknowledges support from the National Science Foundation grant No. 2238875.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2023.104316.

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