Early Pliocene (Zanclean) stratigraphic framework for PRISM5/PlioMIP3 time slices

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ABSTRACT: Global reconstructions of Pliocene climate provide important insights into how the climate system operates under elevated temperatures and atmospheric CO_2 levels. These reconstructions have been used extensively in paleoclimate modeling experiments for comparison to simulated conditions, and as boundary conditions. Most previous work focused on the Late Pliocene interval known as the mid Piacenzian Warm Period (mPWP), the interval originally identified by the U.S. Geological Survey Pliocene Research, Interpretation and Synoptic Mapping Project (PRISM) as the PRISM interval or Mid Pliocene Warm Period. The term Mid Pliocene Warm Period is a misnomer due to changes to the geological time scale, and its use should be discontinued. The Pliocene Model Intercomparison Project (PlioMIP), now in its third phase, is expanding to include a focus on the Early Pliocene (Zanclean). PlioMIP3 experiments will allow comparison of environmental and climatic conditions before and after closure of the Central American Seaway (CAS). PlioMIP3 used the annual insolation pattern at the top of the atmosphere to determine time slices in the Zanclean that have orbital configurations that are most similar to modern. Two have been selected by PlioMIP and adopted by PRISM for inclusion in future studies: PRISM5.1 (4.474 Ma) and PRISM5.2 (4.870 Ma). Here we establish the stratigraphic framework for these Early Pliocene time slices and furnish information to help locate these intervals in proxy records of paleoenvironmental data using oxygen isotope stratigraphy, paleomagnetic stratigraphy, biostratigraphy, and biochronology (calibrated planktic foraminifer and calcareous nannofossil events).

Key Words: Pliocene, PRISM, PlioMIP

INTRODUCTION AND BACKGROUND

The Pliocene has long been the focus of paleoclimate research, and in the more than 30 years since the beginning of targeted work by the U.S. Geological Survey, it remains one of the best natural analogs for near future climate conditions (Zubakov and Borzenkova 1983; Cronin et al. 1984; Cronin 1988; Sarnthein and Fenner 1988; Zubakov and Borzenkova 1988; Dowsett and Poore 1991; Burke et al. 2018) Since the late 1980's the U.S. Geological Survey has had a sustained research effort (Pliocene Research, Interpretation and Synoptic Mapping; PRISM) with the aim to better understand the Pliocene for comparison to future climate conditions. PRISM syntheses of both terrestrial and marine conditions established shifts in land cover types, patterns of wet and dry conditions, elevated sea level, elevated sea surface temperatures (SST), and reduced pole-to-equator temperature gradients (Dowsett et al. 1994).

A second PRISM goal has been to provide digital, global-scale reconstructions of environmental conditions to facilitate climate modeling. Chandler et al. (1994) first used PRISM's Northern Hemisphere reconstruction to drive NASA's Goddard Institute for Space Studies (GISS) climate model (Hansen et al. 1983). With the addition of data from the Southern Hemisphere, including information on sea and land-ice distribution, and establishment of monthly SST estimates (Dowsett et al. 1996; Sloan et al. 1996) were able to explore large scale features of the Pliocene climate using the National Center for Atmospheric Research (NCAR) GENESIS model (Thompson and Pollard 1995). The PRISM2 reconstruction (Dowsett et al. 1999; Dowsett 2007) was used as boundary conditions with versions of the U.K. Meteorological Office General Circulation Model (UKMO) (Haywood et al. 2000, 2002; Haywood and Valdes 2004). The PRISM3 reconstruction was produced in 2010 and the PRISM4 reconstruction in 2016, in close collaboration with the Pliocene Model Intercomparison Project (PlioMIP) and PlioMIP2, respectively.

PlioMIP formed in 2008 in collaboration with PRISM scientists and resulted in the coordination of eight international modeling groups, all using the PRISM3 reconstruction (Dowsett et al. 2010) as boundary conditions for experiments (Haywood et al. 2010; 2011). This first phase of PlioMIP produced or influenced over 100 publications (Haywood et al. 2013a). In 2016 the second phase of PlioMIP was launched (Haywood et al. 2016), having expanded to 17 climate models (Haywood et al. 2020). Both PlioMIP1 and PlioMIP2 made valuable contributions to the Intergovernmental Panel on Climate Change (IPCC) Fifth and Sixth Assessment Reports (AR5 and AR6) (IPCC 2013, IPCC 2021).

Following the successes of previous PRISM/PlioMIP collaborations (Haywood et al. 2016a; Haywood and Dowsett 2021), PlioMIP3 plans include 20 potential experiments utilizing versions of the PRISM4 reconstruction for boundary conditions. An Early Pliocene experiment will address changes to climate introduced by the closing of the Central American Seaway (CAS), the effect of other important ocean gateway changes originally introduced in the PRISM4 reconstruction, and CO_2 forcing during the Pliocene.

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PlioMIP3 will continue to focus on the Late Pliocene (Piacenzian) KM5c (PRISM4/PlioMIP2) time slice (3.205 Ma) while adding two new time slices in the Early Pliocene (Zanclean Stage; 5.33 –3.60 Ma). Based on the astronomical solution of Laskar et al. (2004), Dolan et al. (2022) used the annual insolation pattern at the top of the atmosphere to identify times in the Zanclean having the most similar-to-modern orbital configurations. Two have been identified for inclusion in PlioMIP3 and have been incorporated in the PRISM5 Project as PRISM5.1 (4.474 Ma) and PRISM5.2 (4.870 Ma). The scope of this paper is to clearly define the stratigraphic framework for these new Zanclean time slices and provide the necessary tools for correlation.

PRISM CHRONOLOGY

Understanding the development of the stratigraphic framework surrounding previous PRISM intervals (Dowsett and Robinson 2006; Robinson et al. 2018), is instructive for the recognition and correlation to the PRISM5 intervals identified by PlioMIP3.

Existing PRISM Intervals

The Piacenzian Stage (3.60 to 2.58 Ma) of the Pliocene Epoch (5.33 to 2.58 Ma) was originally selected for detailed study by PRISM because it spans the transition from relatively warm global climates when glaciers were absent or greatly reduced in the Northern Hemisphere to the generally cooler climates of the Pleistocene Epoch (2.58–0.0117 Ma) with expanded Northern Hemisphere ice sheets and prominent glacial-interglacial cycles (Robinson et al. 2018). Downcore studies of marine microfossils (Dowsett and Poore 1990, 1991; Cronin 1991; Dowsett and Loubere 1992; Dowsett et al. 1992; Barron 1992a; 1992b) and several studies of Pliocene high-latitude vegetation (Matthews Jr and Ovenden 1990; Webb and Harwood 1991; Thompson 1991; Fradkina 1991; Volkova 1991) had established this period as a time of warmer-than-modern climate. In addition, it was at the time the oldest interval of global warmth within reach of techniques that were being considered to reconstruct the paleoenvironment.

Initially, the PRISM interval of interest was defined as the period lasting about 300 ky centered on the warm interval at ~3 Ma (using Berggren et al. 1985) that had been identified in micropaleontologic studies. The interval from 3.15 to 2.85 Ma was long enough to be reliably identified and correlated between marine sequences from different ocean basins, independent of climatic characteristics, owing to its proximity to a number of biostratigraphic and magnetostratigraphic events (Berggren et al. 1985; Dowsett 1989).

Dowsett et al. (1999) redefined the PRISM interval for PRISM2, as a period of warm and relatively stable climate (compared to high amplitude glacial –interglacial cycles in the Late Pleistocene) lying between the transition of marine isotope stage (MIS) M2 and M1 and MIS G19 and G18 (Shackleton et al. 1995) in the middle part of the Gauss Normal Polarity Chron, which was equivalent to 3.29 to 2.97 Ma using the updated geomagnetic polarity time scale of Berggren et al. (1995) (text-fig. 1).

The PRISM interval was further refined in PRISM3 (Dowsett et al. 2010), using the marine oxygen isotope stack of Lisiecki and Raymo (2005), to be the period between the transition of MIS M2 to M1 (3.264 Ma) and MIS G21 to G20 (3.025 Ma) in the middle part of the Gauss Polarity Chron (text-fig. 1). This interval ranges from C2An2r (Mammoth reversed polarity subchron) to near the bottom of C2An1 (just above Kaena reversed polarity subchron). This 239-ky interval correlates in part to planktic foraminiferal Zones PL3 (*Sphaeroidinellopsis seminulina* Highest Occurrence Zone), PL4 (*Dentoglobigerina altispira* Highest Occurrence Zone), and PL5 (Atlantic) (*Globorotalia miocenica* Highest Occurrence Zone) or PL5 (Indo-Pacific) (*Globorotalia pseudomiocenica* Highest Occurrence Zone) of Wade et al. (2011).

To improve data-model comparison, PRISM4 adopted a “time slice” approach for reconstruction of marine conditions (Dowsett et al. 2016). PlioMIP2 defined its focus as 3.205 ± 0.01 Ma, which correlates to MIS KM5c (Prescott et al. 2014; Haywood et al. 2016). MIS KM5c was chosen because it is the closest match to Earth’s modern orbit within the PRISM3 time slab. Locating MIS KM5c is relatively straightforward as it correlates to normally polarized sediments (C2An.2n) immediately above the top of the Mammoth reversed (C2An.2r) subchron (3.207 Ma; text-fig. 1). This occurs within calcareous nannofossil Zone NN16 between the last appearances of calcareous nannofossils *Sphenolithus spp.* (3.61 Ma) and *Discoaster tamalis* (2.76 Ma), and within planktic foraminiferal Zone PL3, just below the last appearances of the planktic foraminifera *Sphaeroidinellopsis seminulina* (3.16 Ma) and *Dentoglobigerina altispira* (3.13 Ma).

PRISM5 Interval

Early Pliocene (Zanclean) research and synthesis at the U.S. Geological Survey is being conducted under the Paleoclimate Research: Integrating Systems and Models (PRISM5) Project. PlioMIP3 targets for proxy data include the PRISM4 mid-Piacenzian interval (3.205 Ma, described above and used by PlioMIP2), as well as two new Zanclean targets: 4.474 Ma (PRISM5.1) and 4.870 Ma (PRISM5.2) (text-fig. 1).

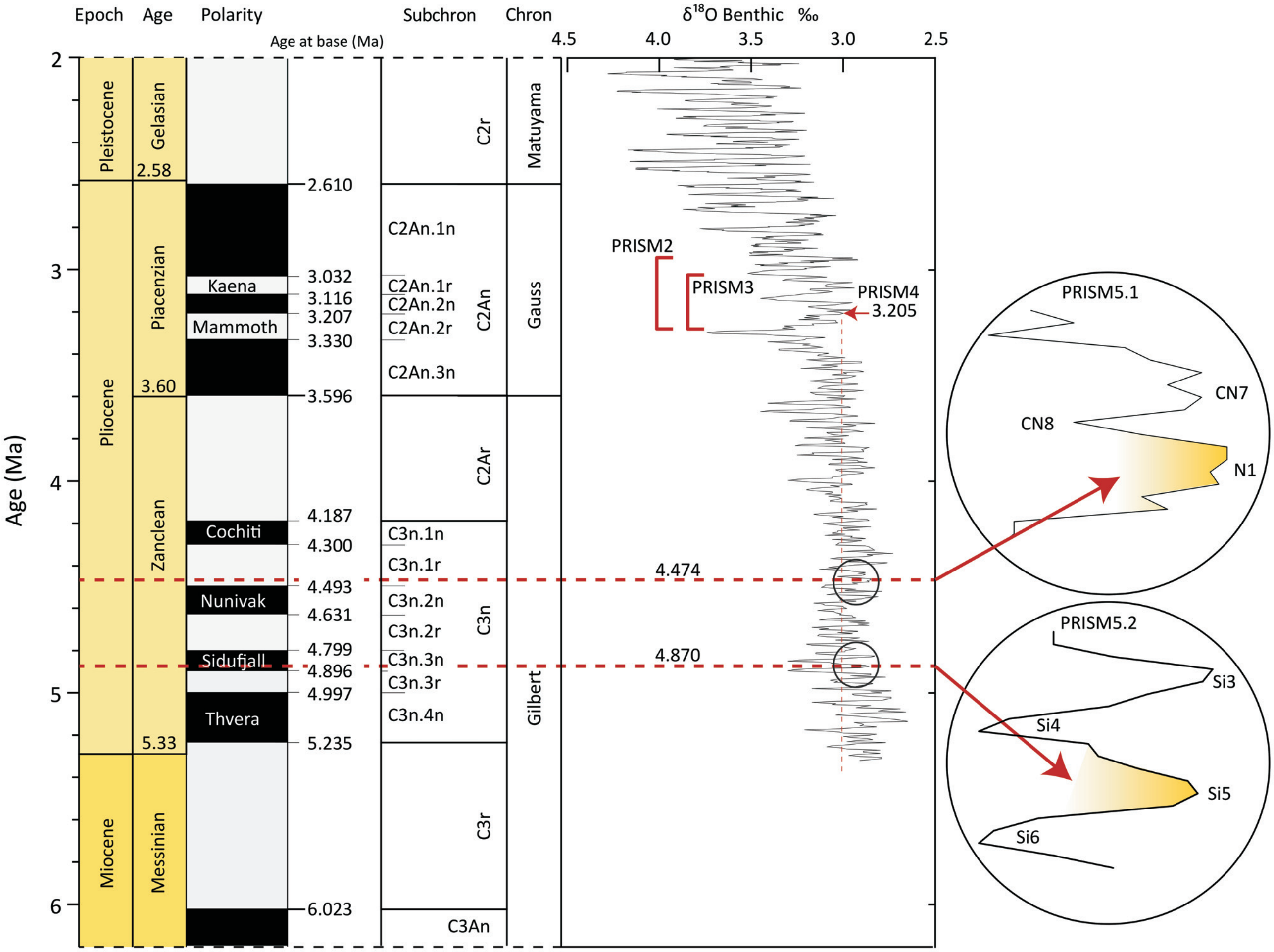
PRISM5.1 (4.474 Ma)

Definition and Age: The PRISM5.1 time slice at 4.474 Ma is defined by its similarity to modern insolation distribution at the top of the atmosphere and coincidence with a negative excursion in the benthic oxygen isotope record (Dolan et al. 2022).

Correlation Tools: PRISM5.1 coincides with MIS N1 which extends from 4.487–4.457 Ma (Lisiecki and Raymo 2005). PRISM5.1 is situated in the Gilbert Polarity Chron, within C3N.1r, the base of which occurs at 4.493 Ma, the top of the Nunivak normal subchron (Gradstein et al. 2020). PRISM5.1 occurs near the top of planktic foraminifera zone PL1 (*Globorotalia tumida/Globoturborotalita nepenthes* Concurrent-range Zone) of Wade et al. (2011), just above the last appearance of *Sphaeroidinellopsis kochi* (4.53 Ma) and the first appearance of *Globorotalia exilis* (4.45 Ma). PRISM5.1 occurs within calcareous nannofossil Zone NN13 (Martini 1971) below the first common occurrence of *Discoaster asymmetricus* (4.04 Ma) and above the last appearance of *Amaurolithus primus* (4.50 Ma).

PRISM5.2 (4.870 Ma)

Definition and Age: The PRISM5.2 time slice at 4.870 Ma is defined by its similarity to modern insolation distribution at the top of the atmosphere and coincidence with a negative excursion in the benthic oxygen isotope record (Dolan et al. 2022).



TEXT-FIGURE 1
Pliocene stratigraphic framework. Magnetostratigraphy and age data from GTS2020 (Gradstein et al. 2020). Benthic δ^{18}O record from Lisiecki and Raymo (2005). Location of PRISM2, PRISM3, PRISM4 and PRISM5 intervals shown with respect to the LR04 isotope stack. PRISM4 corresponds to 3.205 Ma (KM5c), PRISM5.1 and PRISM5.2 intervals correspond to 4.474 Ma (MIS N1) and 4.870 Ma (MIS Si5), respectively.

Correlation Tools: PRISM5.2 coincides with MIS Si5 which extends from 4.883 Ma to 4.860 Ma (Lisiecki and Raymo 2005) (text-fig. 1). PRISM5.2 is situated in the Gilbert Polarity Chron, within C3N.3n, the Sidufjall normal subchron (4.896–4.799 Ma) (Gradstein et al. 2020). PRISM5.2 can be approximately located in planktic foraminifer Zone PL1 (*Globorotalia tumida/Globoturborotalita nepenthes* Concurrent-range Zone) of Wade et al. (2011), between the last appearance of *Globigerinoides seiglei* (4.72 Ma) and the first appearance of *Sphaeroidinella dehiscens* s.l. (5.53 Ma). PRISM5.2 occurs within calcareous nannofossil Zone NN13 (Martini 1971) between the last appearances of *Ceratolithus acutus* (5.04 Ma) and *Amaurolithus primus* (4.50 Ma).

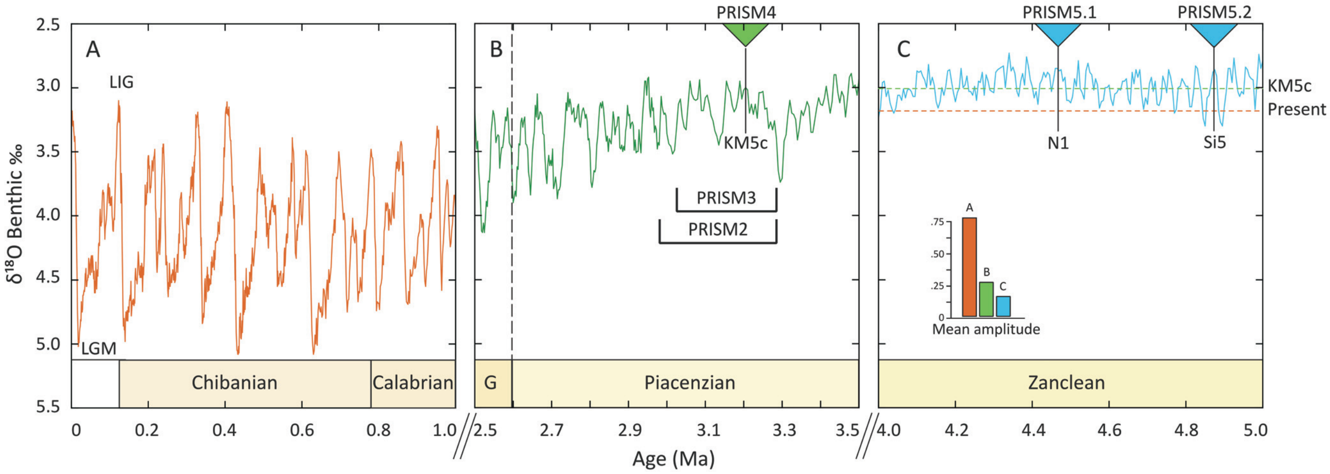
DISCUSSION

Defining the stratigraphic framework surrounding the PRISM5 intervals is key to the identification and correlation of paleoclimate records used for Early Pliocene data–model comparisons. Though we have set forth guidelines to identify PRISM5.1 and PRISM5.2 sediments using MIS records, magnetic polarity and biostratigraphy, the nature of sedimentary records, and of the sediments themselves, can render these identifications challenging. We discuss several challenges below and offer some recommendations based on knowledge gained from previous PRISM work.

Resolution and Stratigraphic Fidelity

Dowsett et al. (2017) established a simple scheme to group time-series based upon two important attributes: methodology used to create age models and resolution achievable through sample density. This qualitative metric was used to characterize the stratigraphic fidelity of alkenone-based records included in PRISM4 work. A survey of 34 published ″UK′37″ temperature records that cross the PRISM5 time slices shows most age models are based upon orbital tuning, which provides the highest measure of stratigraphic fidelity. However, down-core sample spacing for those records ranges from 2 kyr to 280 kyr, with a mean of 78 kyr.

The duration of MIS Si5 is 23 kyr and MIS N1 is 30 kyr. Assuming that a 20 kyr window around the PRISM5.1 and PRISM5.2 time slices shows minimal changes in insolation, as was the case for PlioMIP2 (Haywood et al. 2013b; Prescott et al. 2014), sample spacing of currently available Zanclean sequences is insuffi-



TEXT-FIGURE 2
Comparison of variability in LR04 benthic oxygen isotope stack in three 1-million-year duration windows: (A) 1.0 to 0.0 Ma (brown line), (B) 3.5 to 2.5 Ma (green line), and (C) 5.0 to 4.0 Ma (blue line). Last Interglacial (LIG) and Last Glacial Maximum (LGM) labeled in (A). Positions of the PRISM 2 and PRISM3 time slabs, and PRISM4 time slice, are shown in (B). PRISM5 time slices (PRISM5.1 and PRISM5.2) are shown in (C). Relative amplitude for each segment shown by bar chart for intervals A-C (0.77 ‰, 0.26 ‰ and 0.15 ‰, respectively) in (C). Vertical dashed line near 2.6 Ma in (B) denotes the Piacenzian –Gelasian (Pliocene/Pleistocene) boundary. Horizontal dashed lines in (C) indicate δ^{18}O value for KM5c and present day. Note the breaks in time between panels A, B and C.

cient. For the purposes of locating SST estimates within the PRISM5 time slices, sample spacing should be at least 10 kyr.

Marine sedimentary records are, to some degree, temporally averaged over a range of timescales. Sedimentation rates, bioturbation, and drilling disturbance are just a few of many processes that can modify, distort or disguise signals. Thus, while beyond the scope of this work, it bears remembering that even samples that fall within a ±0.01 My interval around a chosen time slice are each representing mean conditions. Time averaging, non-synchronous spatial variation, and sample spacing place additional limits on the degree to which proxy data can be interpreted and should be accounted for in determining the uncertainty of proxy-based reconstructions.

Low Amplitude Marine Isotope Stages

The amplitude of the benthic δ^{18}O record (Lisiecki and Raymo 2005; Ahn et al. 2017) changes considerably over the last 5 My. The amplitude of the record in the region of the PRISM5 time slices is less than 1/3 of the amplitude during the Late Pleistocene (text-fig. 2). While identification of MIS stages for age models may not be an issue, for those records with low resolution age models but closely spaced samples, identification of the time slice interval will be challenging. Many paleotemperature records used by PRISM4 recorded a strong cooling associated with MIS M2, which was an aid for locating MIS KM5c. There is no such strong enrichment (or depletion) in the 5 Ma –4 Ma segment indicating an easily recognizable climate signal within the Zanclean.

Fossil Event Diachrony

Location of the PRISM5 time slices in marine sequences can be approximated using planktic foraminifer and calcareous nannofossil biostratigraphy as indicated above. However, biostratigraphic zones relay no concept of absolute time (Murphy and Salvador 1999; North American Commission on Stratigraphic Nomenclature 2021) and despite widespread use (e.g. Wade et al. 2011), it must be remembered that calibrated fossil first and last appearances in the stratigraphic record are inherently diachronous (e.g. Dowsett 1989; Lam et al. 2022). Application of biochronologic events in the absence of other independent age data is tenuous and should be avoided. Still, fossil events can be useful as supporting data for more synchronous stratigraphic markers (e.g. identifying a magnetic polarity subchron) but should be relied upon only with detailed knowledge of local fossil zonations.

Data–Model Comparison

Data–model comparisons of the Pliocene have generally focused on point-by-point comparison. Point-based data–model comparisons are valuable but can be misleading due to spatial variability between proxy data and model simulations. It would be more valuable to consider reconstructed versus simulated variations in key meridional and zonal gradients that monitor large-scale features of the climate system. Proxies exist for many environmental variables (e.g., SST, salinity, precipitation, sea-ice cover, productivity, oxygen content, etc.). Inclusion of these variables, in some cases only qualitative, on different scales, provides a more nuanced and holistic reconstruction of the environment and Pliocene climate (Dowsett et al. 2013).

Terminology

Changes enacted by the International Commission on Stratigraphy (ICS) revised the placement of the Pliocene–Pleistocene boundary from the base of the Calabrian Stage (1.801 Ma) to the base of the Gelasian Stage (2.588 Ma), reducing the Pliocene to two, rather than three, Stages (Gibbard et al. 2010). The Piacenzian Stage, containing the PRISM interval, is now the Late Pliocene. Dowsett et al. (2016) formally proposed using "mid-Piacenzian" to correctly refer to the PRISM interval, such as the mid-Piacenzian Warm Period (mPWP). Given the importance of using correct stratigraphic nomenclature, we advise that the use of the term mid-Pliocene to refer to the PRISM intervals or their equivalents (e.g., Ford et al. 2022; Ren et al.

2022; Pontes et al. 2022; Woodhouse et al. 2023; Weiffenbach et al. 2023, etc.) be discontinued. With the addition of the new Early Pliocene (Zanclean) time slices introduced here for PlioMIP3, continued use of "mid-Pliocene" becomes even more confusing. We urge workers to follow International Commission on Stratigraphy (ICS) usage. The PRISM4 (3.205 Ma) time slice should be referred to as Late Pliocene, or more descriptively, mid-Piacenzian. The PRISM5.1 and PRISM5.2 time slices collectively should be referred to as Early Pliocene, or more descriptively, mid-Zanclean, and identified by name: PRISM5.1 (4.474 Ma) and PRISM5.2 (4.870 Ma).

SUMMARY AND CONCLUSIONS

After two iterations of the PRISM/PlioMIP collaboration, the Pliocene is still considered the best "analog" for near future climate (Burke et al. 2018), supporting the rationale for the PlioMIP3 Project. Deep time paleoclimates are not perfect analogs to future climate states. However, past Earth system conditions do offer insight into components of the climate system and can provide scenarios for the warming climate of the near future. The iterative interpretation and comparison of deep-time synoptic reconstructions with model simulations (data-model comparisons) strengthens our understanding of near future conditions that will soon be outside the variability exhibited by historical climate records. This research is essential for understanding past global warmth and analogs for the future.

The Early and Late Pliocene experiments proposed by PlioMIP3 (Haywood et al. 2022) are intended to enhance our understanding of both past and future climate change. The stratigraphic and chronologic framework within which proxy data are reconstructed and compared are critical to the results and interpretations made.

Providing high-resolution records from the PRISM5.1 and PRISM5.2 intervals for comparison with PlioMIP3 experiments represents a new challenge for the paleoclimate data community. Early Pliocene (Zanclean) targets are included in PlioMIP for the first time, and not as many paleotemperature records exist for the Zanclean as they do for the Piacenzian. The PRISM5 time slices can be more difficult to locate than the PRISM4 KM5c time slice due to the low amplitude nature of early Pliocene δ^{18}O records and lack of distinctive isotopic events.

We have furnished information to help locate the PRISM5.1 (4.474 Ma) and PRISM5.2 (4.870 Ma) time slices in marine units using the structure of the oxygen isotope record, paleomagnetic reversal stratigraphy, and marine biochronology (calibrated microfossil events).

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