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Journal:	*Philosophical Transactions A*
Manuscript ID:	RSTA-2012-0515
Article Type:	Research
Date Submitted by the Author:	11-Dec-2012
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Issue Code: Click here to find the code for your issue.:	DM1011
Subject:	Atmospheric science < EARTH SCIENCES, Climatology < EARTH SCIENCES, Geology < EARTH SCIENCES, Oceanography < EARTH SCIENCES, Palaeontology < EARTH SCIENCES
Keywords:	Pliocene, Climate models, Climate Sensitivity, Earth System Sensitivity

ON THE IDENTIFICATION OF A PLIOCENE TIME SLICE FOR DATA-MODEL COMPARISON

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SUMMARY: The characteristics of the mid-Pliocene Warm Period (mPWP: 3.264 to 3.025 Ma BP) have been examined using geological proxies and climate models. Whilst there is agreement between models and data, details of regional climate differ. Uncertainties in prescribed forcings and in proxy data, limit the utility of the interval to understand the dynamics of a warmer than present climate or evaluate models. This uncertainty comes, in part, from the reconstruction of a *time slab* rather than a *time slice,* where forcings required by climate models can be more adequately constrained. Here we describe the rationale and approach for identifying a time slice(s) for Pliocene environmental reconstruction. A time slice centred on 3.205 Ma BP (3.204 to 3.207 Ma BP) has been identified as a priority for investigation. It is a warm interval characterised by a negative benthic oxygen isotope excursion (0.21-0.23‰) centred on Marine Isotope Stage KM5c (KM5.3). It occurred during a period of orbital forcing which was very similar to present-day. Climate model simulations indicate that proxy temperature estimates are unlikely to be significantly affected by orbital forcing for at least a precession cycle centred on the time slice, with the North Atlantic being an important exception.

Keywords: Pliocene, climate models, Climate Sensitivity, Earth System Sensitivity.

1. INTRODUCTION

1.1 The importance of the mid-Pliocene warm period

Compared to the Pleistocene, the mid-Pliocene warm period represents an interval of relatively warm and stable climate between 3.264 and 3.025 Ma BP (Dowsett et al., 2010; Haywood et al., 2010). According to the geological timescale of Gradstein et al. (2004), it sits within the Piacenzian Stage of the Late Pliocene. The interval is synonymous with the PRISM time slab (Pliocene Research Interpretation and Synoptic Mapping), for which a global data set of palaeoenvironmental conditions has been developed by the US Geological Survey and international collaborators (e.g. Dowsett et al., 2010; Haywood et al., 2010). The PRISM Project has documented patterns of sea-surface temperature (SST; e.g. Dowsett et al., 1994, Dowsett et al., 1996; Dowsett et al. 2009) and land cover (e.g. Thompson and Fleming, 1996; Salzmann et al. 2008) using multiple proxy techniques, as well as reconstructing deep ocean temperatures (e.g. Dowsett et al., 2009). Estimates of sea level as well as topographic differences between the mid-Pliocene and present-day have been produced (e.g. Dowsett and Cronin, 1990; Sohl et al., 2009). These reconstructions were developed with a dual purpose; to provide greater understanding of climate and environments in a warmer world, and to provide geographically continuous boundary conditions to facilitate Pliocene climate model experiments (Dowsett et al. 2010).

Until 2004, Atmospheric General Circulation Models (AGCMs) were the only type of climate model applied in a mid-Pliocene context (e.g. Chandler et al., 1994; Sloan et al., 1996; Haywood et al., 2000). These models required global information on SST, sea-ice cover as well as land cover, as they are not predicted variables in such models. In later years single-site SSTs and land cover data are increasingly being used to evaluate model outputs, as climate models have developed and can now predict SSTs and vegetation (coupled atmosphere-ocean-vegetation climate models – AOGCMs and AOVGCMs). Therefore, the use of the PRISM data set is evolving from specifying boundary conditions in models towards a model evaluation approach (Haywood and Valdes, 2004; Lunt et al., 2010; Dowsett et al., 2011; Dowsett et al., 2012).

Both geological data, as well as model outputs, have shed considerable light on the nature of mid-Pliocene climate and environments. During warm phases of the mid-Pliocene, highlighted by negative excursions in $\delta^{18}O$ from benthic foraminifera, Antarctic and/or Greenland ice volume may have been reduced (Lunt et al., 2008; Hill et al., 2010; Naish et al., 2009; Pollard and DeConto, 2009; Dolan et al., 2011). Between 2.7 to 3.2 Ma BP the peak sea-level is estimated to have been 22 ± 10 m higher than modern (Miller et al., 2012), and it appears that SSTs were warmer (Dowsett et al., 2010), particularly in the higher latitudes and upwelling zones (e.g. Dekens et al. 2007; Dowsett et al., 2012). Sea-ice cover also declined substantially (e.g. Cronin et al., 1993; Polyak et al. 2010; Moran et al., 2006). On land, the global extent of arid deserts decreased and forests replaced tundra in the Northern Hemisphere (e.g. Salzmann et al., 2008). Based on model predictions the global annual mean temperature may have increased by more than 3°C (e.g. Haywood and Valdes, 2004). Meridional and zonal temperature gradients were reduced, which had a significant impact on the Hadley and Walker circulations (e.g. Haywood et al., 2000; Chan et al., 2011). The East Asian Summer Monsoon, as well as other monsoon systems, may have been enhanced (e.g. Wan et al. 2010).

Given the abundance of proxy data, the mid-Pliocene has become a focus for data/model comparisons that attempt to analyse the ability of climate models to reproduce a warm climate state in Earth history (e.g. Haywood and Valdes, 2004; Salzmann et al, 2009; Dowsett et al., 2011; Dowsett et al., 2012). Furthermore, the mPWP has been proposed as an important interval to assess the sensitivity of climate to current or near future concentrations of carbon dioxide (CO_2) in the longer term (hundreds to thousands of years; Lunt et al., 2010). This links directly to the emerging paradigm of Earth System Sensitivity (Hansen et al., 2008; Lunt et al., 2010). Unlike traditional Climate Sensitivity, which is defined by the equilibrium global mean temperature response to a doubling of atmospheric CO_2 from short term feedbacks (*Charney Sensitivity*; Charney et al., 1979), Earth System Sensitivity includes feedbacks from slower responding components of the climate system, including the ice sheets and vegetation (Lunt et al., 2010). These feedbacks may eventually alter the global mean temperature response to a given change in CO_2 concentration. Estimates of Earth System Sensitivity, based on examining a past warm interval like the Pliocene, could provide a means to develop CO_2 emission reduction targets and climate stabilisation scenarios, which would enable the global mean temperature change to remain below the European Union defined threshold of 2°C, in the long term (Meinshausen et al., 2009; Haywood et al., 2011).

1.2 Limitations of a time slab approach

PRISM appreciated the challenges of providing AGCMs with a truly global data set of environmental boundary conditions. Inherent limitations that existed at the time of correlating one marine or land site to another over vast geographical distances, ruled out the identification of a discrete time slice in the Pliocene (Dowsett and Poore, 1991). Instead PRISM took a pragmatic approach of establishing a time slab to which the ages of marine or terrestrial sites could be more confidently attributed (Dowsett and Poore, 1991). It also naturally increased the potential amount of geological data that could be incorporated, and would therefore underpin the environmental reconstruction.

Whilst this approach solved one problem it created another. Climate and environmental variation (including sea level) during the mid-Pliocene is likely to have been smaller than for the last two million years, yet clear variations do occur over orbital timescales (e.g. Lisiecki and Raymo, 2004; Leroy and Dupont, 1994; Haywood et al., 2002). Yet in terms of boundary conditions for climate models, or for proxy temperature estimates used for climate model evaluation, a single SST value and a single land classification is generally required.

In response to this PRISM established the methodology of SST Warm Peak Averaging (Figure 1; Dowsett and Poore, 1991), where warm inflections in down core measurements of SSTs are calculated. Foraminifera assemblages that achieve a sufficiently high communality cut-off (0.7 or greater) are retained and then averaged to produce a single SST value per core site (Dowsett and Poore, 1991). On land, evidence for variability in vegetation type over orbital time scales is less common, and the window of time which has to be used to generate a satisfactory distribution of land cover data is larger (one million years - the entire Piacenzian Stage). If information on vegetation variability is available, then the biome representing the warmest climatic conditions has been selected and placed into the land cover reconstruction (Salzmann et al. 2008).

So what exactly does the PRISM environmental reconstruction represent? From site to site it is an average of warm climate signals that occurred during a time slab. It should not be considered as a reconstruction of environmental conditions that existed together at a discrete moment in time. In terms of mid-Pliocene climate modelling studies using AGCMs this does not present a significant problem. The PRISM reconstruction allows AGCMs to examine what a global average warm climate during the mid-Pliocene might have looked like (Chandler et al., 1994; Sloan et al., 1996; Haywood et al., 2000). However, outputs from AOGCMs have highlighted a clear disconnection between the proxy data, which is representative of a time slab, and relatively short model integrations that predict a climate state based on constant external forcing (Dowsett et al., 2012). The motivation for defining a new time slice is the hypothesis that a component of this model-data inconsistency is related to the time slab nature of the proxy data.

Whilst there have been a number of attempts to evaluate AOGCMs against the PRISM data set, the fact that data and models are not reproducing the same objective, i.e. a discrete moment in time during the mPWP, makes the identification of any true model bias impossible (e.g. Haywood and Valdes, 2004; Salzmann et al., 2009; Dowsett et al., 2011; Dowsett et al., 2012). In reality a climate model simulation run for 1000 integrated years, using only a single realisation of orbit, CO_2 and other forcings cannot reproduce a reconstruction of average warm climate conditions that is a product of multiple and changing/interacting forcing mechanisms.

What does this imply for previous mid-Pliocene based estimates of Earth System Sensitivity? Changes in the Earth's orbit are not relevant to calculations of either Climate or Earth System Sensitivity. If reconstructed changes in global ice volume or vegetation distribution are largely or even partly a function of orbital variability rather than $CO_{2,}$ the utility of the mid-Pliocene warm period for understanding the sensitivity of climate in the context of future climate change is diminished. Transient mid-Pliocene climate simulations using an Earth System Model of Intermediate Complexity are becoming available. Here CO_2 forcing and orbital forcing have been imposed in isolation and in concert, and have suggested that a significant percentage of the additional feedback to global temperature derived from changes in vegetation cover and ice sheet extent are attributable to orbital forcing (Ganopolski et al., 2011).

In summary, the PRISM time slab has given the scientific community insights into the nature of climate and environments of the time. However, the demands of modern data/model comparison indicate that progress in the future relies on the identification of a discrete time slice, or slices, for investigation within the Pliocene epoch.

2. DEFINING A NEW TIME SLICE(S)

2.1 Rationale and criteria for selection – where in the Pliocene?

The benthic oxygen isotope record of Lisiecki and Raymo (2005; LR04) provides a view of changes in ice volume and bottom water temperature over the last five million years (Figure 2). From the Pliocene section of the record, what interval of time should be selected to provide the focus for a new Pliocene time slice reconstruction? Ultimately, the selection depends upon the scientific questions posed, as well as the data required to effectively answer them.

Pragmatism suggests that the time slice is selected from within the existing PRISM time slab (Dowsett et al., 2010), as this provides the optimal starting point in terms of the availability of proxy data to underpin a new reconstruction. Choosing a time slice within the Late, rather than Early, Pliocene has added advantages in terms of reducing the potential for significant deviations in topography and ocean gateway configurations from present-day. These factors cannot be easily determined (i.e. the Central America Seaway and the western cordillera of North and South America; e.g. Moucha et al., 2009; Sarnthein et al. 2012; Bartoli et al., 2005), and therefore introduce unnecessary uncertainty into a climate model's experimental design. Identifying a time slice in the Late Pliocene also reduces the potential for non-stationarity of environmental tolerance to bias geological proxies. In other words, the further back in time the greater the potential for organisms/biota to have existed in different environments than they do today (Des Marais and Juenger, 2010; Murray, 2001).

The PRISM project's aim is to understand environments and climates of a warmer world (Dowsett et al., 1999). This scientific need has not diminished over the last 20 years; in fact in the context of current estimates of future climate change it is growing ever more acute (IPCC, 2007). Thus, a warm episode defined by a negative benthic oxygen isotope excursion in the LR04 stack most likely representing a sea level high stand, within the current

PRISM time slab, is most appropriate for the selection of the first Pliocene time slice.

2.2 Rationale and criteria for selection – where in the PRISM time slab?

Given that the scenario of a discrete time slice falling on a biostratigraphic boundary or magnetic reversal is unlikely, identification will rely upon orbitally tuned high-resolution benthic oxygen isotope records. Assuming an equal availability of proxy data for any warm interval of the current PRISM time slab, the selection of which warm episode can be determined by a number of additional criteria. These criteria recognise the challenges of stratigraphically resolving a time slice, whilst at the same time attempting to reduce the uncertainty in both reconstructing and modelling the time slice. These include:

1. Selection of a negative oxygen isotope excursion of significant magnitude to identify an interval that was substantially warmer and had higher sea level than present-day, and where the climate anomaly is significant producing a favourable signal to uncertainty ratio
2. Selection of a time slice that falls at or very close to the peak in the identified benthic oxygen isotope excursion, to facilitate the time slice's identification in high resolution benthic oxygen isotope records
3. Selection of a negative oxygen isotope excursion of significant duration (thousands of years) to provide as large a time window as possible facilitating correlation, and allowing the climate to respond sufficiently to the forcing in this interval
4. Selection of a time slice that is at or close to CO_2 estimates from proxy records, to better constrain the range of CO_2 values that should be imposed within climate models.

A careful examination of orbital parameters is warranted not just by the demands of chronology and correlation, but also in terms of the forcing imposed within climate models.

An immediate question emerges; what kind of orbital forcing should be imposed. For example, is a situation akin to the mid-Holocene or the Last Interglacial required? In these cases the response of climate models to a significant change in insolation at the top of the atmosphere is studied (e.g. Otto-Bliesner et al., 2006). Would a better result come from trying to identify a time slice which was warm and yet orbital forcing was the same, or very similar, to present-day? If a warm episode within the current PRISM time slab can be identified, and it displays a modern or close to modern orbit, it removes or reduces an additional variable from the interpretation of the geological data and climate modelling results. It also simplifies the process of attributing what proportion of the global annual mean surface temperature increase, simulated by climate models, comes from different forcing mechanisms (e.g. Lunt et al., 2012). Finally, it enhances the potential for the time slice to provide more relevant information in the context of Climate and Earth System Sensitivity in the future, since the orbital forcing is the same or very similar to present-day. If an interval exists in which eccentricity, obliquity and precession do not vary substantially around a time slice, orbital forcing will have a limited effect in creating variability in mean annual and seasonal temperatures. Focusing on such a time window would have the added advantage of helping to limit the impact on proxy temperature estimates of orbital variability, brought about by imperfect correlation to a time slice.

3. ASTRONOMICAL SOLUTIONS AND ORBITAL FORCING

3.1 Astronomical solutions

To identify a warm episode within the existing PRISM time slab with modern or near modern patterns of insolation, it is necessary to calculate the planetary and precessional elements of the Earth for the entire time slab. Numerous astronomical solutions currently exist and provide the fundamental astronomical parameters of eccentricity, climatic precession, and obliquity needed for climate models (e.g. Berger and Loutre, 2002; Laskar et al., 2004). The level of agreement that exists between solutions in calculating astronomical parameters for past periods in earth history suggests that, as tools, they are sufficiently reliable to be used in palaeoclimate studies spanning the last 30 million years (Berger and Loutre 1992; Laskar et al., 1993; Laskar et al., 2004).

3.2 Orbital forcing through the PRISM time slab

3.2.1 The La93 versus La04 orbital solution

The LR04 stack (Lisiecki and Raymo, 2005) was developed using a non-linear ice model that used insolation forcing derived from the Laskar et al. (1993; La93) astronomical solution. Since then, an updated version of the Laskar solution has been produced (Laskar et al., 2004; La04). The La04 solution has been improved with respect to La93 by using a direct integration of the gravitational equations for the orbital motion, and by improving the dissipative contributions, in particular in the evolution of the Earth-Moon System (Laskar et al., 2004). Before the La04 solution can be used in concert with the LR04 stack to help identify a time slice(s) for reconstruction, we must determine that the solutions provided by La93 or La04 are the same or very similar. Figure 3 shows the difference between the two solutions at 65° N on the 21st June (the forcing function used in the simple non-linear ice model of LR04). During the PRISM time slab, the phasing between the two solutions is in strong agreement, as well as the magnitude of the insolation variation. Thus, we are confident in our use of the La04 solution to investigate orbital forcing during the PRISM time slab.

3.2.2 La04 reconstructions of insolation

Variations in eccentricity, precession and obliquity according to La04 are shown in Figure 4b and 4c for the period 2.95 to 3.35 Ma BP. This more than encompasses the PRISM time slab. A notable feature is a low in eccentricity values between 3.20 to 3.30 Ma BP, with correspondingly low modulations in precession. Across the PRISM time slab, insolation as a global annual mean derived from La04 varies by a maximum of 0.51 Wm^{-2} (Figure 4f). Largest variations are apparent younger than 3.2 Ma BP, with values that are generally closest to modern occurring prior to 3.2 Ma. We have also calculated the difference from present-day insolation at the top of the atmosphere (TOA) at each 1000 year time step between 2.95 and 3.35 Ma. This allows us to also take into consideration how incoming insolation varies as a function of latitude and month in comparison to present-day.

3.2.3 Statistical evaluation of La04 results

Our objective is to identify times within the PRISM time slab where the TOA insolation distribution is most similar to that of present day. In order to differentiate between the 400 insolation patterns produced, we evaluate the spatial similarity between the past and the present. The match between the spatial patterns has been evaluated in terms of correlation (r), root-mean-square (RMS) difference, and the ratio of the variances (standard deviation). A perfect solution under this definition would have no error as computed by the RMS, would perfectly correlate with the present (r=1), and have the same standard deviation.

We only consider solutions within the first ten discrete minima in RMS error as potential candidates for the first Pliocene time slice. This equates to an RMS error of < 5 Wm^{-2}. RMS offers the clearest distinction between the 400 potential solutions as standard deviation does not vary significantly amongst the ensemble. Each of the ten defined minima in RMS error can include a number of individual orbital solutions that have very similar skill in matching the modern insolation distribution and are closely associated in time (see Table 1). Best-fit orbital solutions from each discrete minima in RMS error are highlighted as vertical dashed lines on Figure 4.

Section 2.2 outlined the attributes that the chosen time slice should exhibit. Table 1 summarises the relative attributes of the identified ten discrete minima in RMS error, as well as the best-fit solutions. None of the best-fit time solutions identified in our analysis are located at the lightest δ^{18}O excursion seen in the LR04 stack for the PRISM time slab (Figure 4a), as this is associated with a large change in orbital forcing from present-day (Figure 5b). Although there are multiple candidates for a Pliocene time slice reconstruction (e.g. within RMS error minima 5, 7 and 8; see Table 1), orbital solutions in the 4th discrete minima in RMS error (3.204 to 3.207 Ma BP) provide the best overall solution given the rationale and criteria stated in section 2.

3.3 Characteristics of the first Pliocene time slice

The chosen time slice sits in the normal polarity of the Gauss Chron between the Kaena (above) and Mammoth (below) reversals (Figure 2). The peak deviation in benthic δ^{18}O is centred on Marine Isotope Stage KM5c (or KM5.3). The 0.21 to 0.23‰ deviation in δ^{18}O could reflect a 21 to 23 m sea-level rise above modern (assuming 0.1‰ equates to ~10 m of sea level rise), providing that the signal is purely a function of ice volume rather than any change in deep ocean temperatures. Assuming the near-total loss of the West Antarctic and Greenland Ice Sheets (a reasonable initial premise given proxy data and model outputs; Naish et al., 2009; Pollard and DeConto, 2009; Dolan et al., 2011; Lunt et al., 2008), volume reduction from the East Antarctic Ice sheet is a moderate 6 or 7 m of ice volume equivalent. This general interpretation of sea-level from the LR04 stack is supported by a recent synthesis of sea-level records between 2.9 and 3.3 Ma BP by Miller et al. (2012). At ~3.205 Ma BP the Miller et al. (2012) synthesis indicates a maximum sea-level rise of 25 m ± 10 m (derived from mg/ca ratios of deep marine ostracods; Dwyer and Chandler, 2009). A mean of multiple sea-level records for approximately the same time indicates a peak sea-level rise of ~ 22 m ± 10 m.

During the time slice incoming insolation is close to the modern distribution both seasonally and regionally (Figure 4c; Table 2). Eccentricity and precession are near zero, and obliquity remains near modern before and after the time slice. Therefore, the time slice is centred upon an interval with a relatively stable orbit during which the distribution of insolation was close to modern (i.e. RMS error is low and the correlation coefficient is high).

Available proxy data for atmospheric CO_2 (see Bartoli et al. 2011 for a summary) places an upper limit of ~400 ppmv, with a cluster of four measurements within 100 ka of the time slice using three different proxy techniques (alkenones, boron isotopes and stomatal density) indicating a range between 300 to 380 ppmv. These concentrations are broadly supported by new high resolution alkenone-proxy CO_2 measurements presented in this volume (Badger et al. this volume).

4. CURRENT STATE OF KNOWLEDGE AND FUTURE OUTLOOK

4.1 Availability of marine and terrestrial proxy data

Recent advances in deep sea drilling techniques have made possible the generation of numerous high-resolution orbitally-tuned chronologies for Neogene marine sequences. Demand for finer resolution deep-time palaeoclimate analysis makes this the norm rather than a rarity. The current PRISM SST data set has 115 sites (Dowsett et al., 2012; Figure 6a) focused on a time slab of ~240 ka based upon the warm peak averaging technique (Dowsett and Poore, 1991; Dowsett and Robinson, 2006). The next PRISM SST reconstruction which is in development (PRISM4) represents more than a two order of magnitude increase in resolution with palaeoceanographic reconstruction. Preliminary analysis of available material for reanalysis from the PRISM project suggests no fewer than 30 globally distributed SST sites may contribute to the first phase of time slice reconstruction for 3.204 to 3.207 Ma BP (Figure 6a and Table 3). These sites range from ~50° south to ~60° north latitude and sample all major ocean basins, with approximately half the sites confined to the low latitudes. In addition to the re-sampling of PRISM material, state-of-the-art high-resolution SST records, albeit of variable resolution, are available for the time slice in the published literature (Figure 7). In total thirteen SST records are currently available sampling the high-latitudes (IODP sites 1090, 607, 982 and 882), upwelling regions (IODP sites 1082, 847, 847 and 846) and equatorial regions (IODP sites 662, 722, 763, 214 and 806).

Salzmann et al. (2008) describes terrestrial proxy data, 202 globally distributed sites, which were synthesized to create a global land cover reconstruction for the entire Piacenzian Stage. Figure 6b and Table 4 shows the distribution of 26 terrestrial localities from the original data set of 202 sites, which potentially may be able to provide vegetation data to evaluate climate model predictions for the Pliocene time slice. In reality correlating terrestrial data to any Pliocene time slice is not possible with the same degree of confidence as the marine proxy data. This will require consideration when terrestrial data/model mismatches are highlighted.

In the marine realm a plausible strategy for identifying the time slice would be to initially identify the MIS M2 and sample forward in time (i.e. produce a time series) at the highest practical sampling resolution in each core. MIS KM2 provides another isotopic marker useful for reference after the time slice itself. We term this interval between MIS M2 and KM2 the *Zone of Investigation* (see Figure 7). Limitations in correlation may create situations in which multiple temperature estimates can be plausibly attributed to the time slice. In such circumstances the appropriate information from the point of view of data/model comparison is the range in absolute reconstructed temperatures (or range in temperature differences) rather than an average. If a multi-proxy approach is adopted the range in temperature estimates from each proxy-method should be clearly stated.

4.2 Enduring uncertainties, challenges and new opportunities

Whilst the identification of discrete time slices reduces variability in proxy climate data used to evaluate models, and will place tighter constraints on the design of climate model experiments, it is not a panacea for the Pliocene. Moving to a time slice will lead to a reduction in the amount and geographical spread of proxy data available for data/model comparison, particularly in the terrestrial realm. Issues of bioturbation, varying accumulation rates, and the potential for different proxy methods to monitor different parts of the water column in different parts of the year all remain (Dowsett and Robinson, 2006). Furthermore, whilst the selection of the first Pliocene time slice was partly made on the fact that the interval will minimise the potential bias introduced by orbital forcing, it does not remove it entirely (see Figure 5c). This means that orbital forcing will change to a degree through and around the studied time slice. Therefore, time slice sensitivity experiments with climate models are warranted to fully explore orbital influences on regional climates.

To provide an initial assessment of the degree to which differences in insolation calculated for the 3205 ka BP time slice compared to modern can affect a climate model's simulation of Pliocene climate, we show the difference in mean annual as well as seasonal average surface air temperatures (SATs) between two Pliocene simulations using the Hadley Centre Coupled Climate Model Version 3 (HadCM3; Figure 8). The deviation in SATs as an annual and seasonal mean is no more than 1°C in most ocean and terrestrial regions. The majority of the differences are not statistically significant at a 95% confidence interval.

To provide an initial assessment of how stable climate could have been in response to orbital forcing around the time slice itself, we show results from two further sensitivity studies in which the model has been run with orbital forcing equivalent to 3195 and 3215 ka BP, 10 ka either side of the identified time slice at 3205 ka BP. Compared to mean annual SATs simulated for the time slice, simulations for 3195 and 3215 ka BP rarely differ by more than 1°C. The predicted differences are normally insignificant at a 95% confidence interval. One exception to this is in the North Atlantic where differences reach 2 to 3°C and are statistically significant (Figure 8). The pattern of SAT anomalies is akin to an NAO dipole (North Atlantic Oscillation) and the results even appear to show the Pacific branch of AO (Arctic Oscillation). This suggests a few scenarios for the genesis of the changes in the North Atlantic. They may represent a temporal shift of normal NAO during model spin up that is not removed by the t-test because of long period oscillations. Alternatively, they may represent changes in modes of interannual variability, or be indicative of significant orbital impact on NAO. Providing that these differences are not a model or statistical artefact, the results imply that in the North Atlantic correlation to the time slice would have to be better than 10 ka to keep orbital forcing biases on temperature to less than 3°C. Seasonally larger changes that are statistically significant are predicted. For example, 3°C over Antarctica during the Southern Hemisphere summer and up to 3°C over land in the simulation for 3195 ka in the Northern Hemisphere summer (Figure 8). These seasonal differences will not affect proxy temperature estimates if the proxy itself truly provides an estimate of mean annual temperature. However, they should be considered in data/model comparisons if a proxy technique has the potential to be biased to a temperature reconstruction for a particular season. Therefore, the selection of the time slice and its characteristic stability in orbital forcing immediately before and after creates a time window in which palaeo-temperature information can be imperfectly correlated to the time slice itself, but may still be more or less representative of the general conditions which existed during the time slice. We term this a *Zone of Tolerance* (see Figure 7).

To place these differences in climate due to orbital variability around the Pliocene time slice in context, we have performed a final experiment with HadCM3 in which an orbital forcing appropriate to 3060 ka BP was prescribed. The 3060 ka BP PlioMAX peak (or super interglacial event) is characterised by one of the lightest benthic oxygen isotope excursions evident in the entire PRISM time slab (Marine Isotope Stage K1; Raymo et al. 2011). 3060 ka BP is characterised by the La04 orbital solution as displaying a dramatically different profile of insolation by month and latitude compared to either present-day or the identified Pliocene time slice at 3205 ka BP (see Figure 5). It is also an interval in which the total amount of insolation as a global annual mean differs from present-day, or the 3205 ka BP time slice, by +0.5 Wm^{-2} (see Figure 4). Figure 8 shows the model-predicted differences in annual and seasonal mean surface air temperature for 3060 ka BP compared to the Pliocene time slice at 3205 ka BP. As an annual mean SAT differences can exceed +3°C and are almost always statistically significant at a 95% confidence level. This general increase in mean annual temperature is partly caused by the 0.5 Wm^{-2} enhancement in annual global mean insolation calculated for 3060 ka BP compared to 3205 ka BP. It is also strongly influenced by much larger changes in seasonal insolation patterns and surface air temperatures that often exceed +5°C, particularly during the Northern Hemisphere summer months (JJA) over the land. If any proxy data included in either the PRISM3D marine or terrestrial environmental reconstructions is actually representative of 3060 ka BP, it would not be expected to concur with model simulations for the Pliocene set up with a modern, or essentially modern, profile of insolation. This analysis also suggests that 3060 ka BP is inappropriate as a means to assess Climate or Earth System Sensitivity due to the more significant orbital overprint on surface air temperatures (see Figures 5 and 8).

Even with greater certainty in the orbital forcing given to models for the Pliocene, many of the challenges in deriving certain boundary conditions for models remain constant across a time slab or time slice approach. Perhaps the most challenging is the initial state of the ice sheets. The time slice approach also means that the application of a time slab-based vegetation reconstruction as a boundary condition becomes more difficult to justify, implying that future experiments for time slices during the Pliocene will be increasingly dominated by the use of coupled ocean-atmosphere-vegetation models, where vegetation is a predicted rather than a prescribed element.

Ultimately, given the uncertainties in prescribed forcing, even for defined time slices, only a limited amount of information can be gained by comparing only one realisation of Pliocene climate from a climate model to proxy data. A comprehensive programme of well justified time slice sensitivity experiments with climate models is required and can be examined in concert with the proxy data during future data/model comparisons. The number of sensitivity experiments that are likely to be required even for a Pliocene time slice will be less than the requirements of the current PRISM time slab. Nevertheless, the number required will remain demanding computationally, even for full complexity climate models of even intermediate resolution. Therefore, other techniques to sufficiently explore uncertainty space with climate models, such as a Latin Hypercube approach that has been successfully applied in palaeoclimate research (e.g. Gregoire et al., 2011), may be required. The implementation of such a strategy will generate progressively more rigorous data/model comparisons, where an identified signal or residual may highlight a deficiency in climate model predictions for the Pliocene with greater confidence.

Finally, from the point of view of understanding the Pliocene it is essential to develop a better appreciation of how climate varied through time. We have identified other time slices prior to 3.2 Ma BP that provide potential targets for environmental reconstruction. Of particular interest is the evolution of Pliocene climate and environments from the M2 to KM2 'glacial' events (the *Zone of Investigation* identified in Figure 7). Until more is understood about how climate evolved towards and away from the Pliocene time slice, we will not be able fully understand what the time slice represents. Through increasing our understanding of the nature and variability of Pliocene climates we can understand the Pliocene world more completely, and at the same time, apply the Pliocene as test for models used to predict future climate change with increasing certainty.

5. CONCLUSIONS

In this study we outline the rationale and criteria for the definition of a discrete time slice for environmental reconstruction during the mid-Pliocene Warm Period (mPWP). The mPWP time slab concept, developed by the US Geological Survey PRISM Project (Pliocene Research Interpretation and Synoptic Mapping), has provided a means to explore and understand climate and environments of a warm phase in Earth history in considerable detail. However, a change in methodology to time slice reconstructions, which have been used so successfully in the Quaternary, is necessary to reduce uncertainties in environmental reconstruction as well as climate/environmental modelling. Whilst a range of time slices should be studied that examine different facets of Pliocene climate (e.g. periods with strong orbital forcing or Pliocene 'glacial' events), the highest initial priority is to examine a warm period in which orbital forcing was the same or very similar to present-day. This is justifiable given the current requirements to better understand Climate and Earth System Sensitivity, and to robustly evaluate models used for climate change prediction.

A suitable time slice representative of a warm event or 'interglacial' within the existing PRISM time slab has been identified through the calculation and statistical evaluation of orbital forcing using the La04 orbital solution. The time slice is centred on a negative peak (0.21-0.23‰) in the LR04 benthic oxygen isotope stack at Marine Isotope Stage KM5c (KM5.3) at 3.204 to 3.207 Ma BP. Limits of chronology and correlation mean that the time slice may not be resolved in marine records from different ocean basins to a window of only a few thousand years. However, between 3.215 and 3.195 Ma BP orbital forcing was similar to present-day. Atmospheric CO_2 may have peaked at approximately 400 ppmv, with CO_2 proxies supporting a common range of between 300 and 380 ppmv. Whilst challenges and uncertainties will remain from a modelling and environmental reconstruction stand point, the reduced temporal range of a time slice facilitates the construction of more focussed sensitivity studies using climate models. Time slices are also short enough to contemplate performing fully transient simulations with a full complexity intermediate resolution climate model in the future.

ACKNOWLEDGEMENTS

A.M.H., A.M.D and S.J.P acknowledge that the research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013) / ERC grant agreement no. 278636. A.M.D acknowledges the UK Natural Environment Research Council (NERC) for the provision of a Doctoral Training Grant. H.J.D. acknowledges the support of the US Geological Survey Climate and Land use Change Research and Development Program. The paper forms part of the US Geological Survey PRISM project (Pliocene Research Interpretations and Synoptic Mapping). D.J.H. acknowledges The Leverhulme Trust for the provision of an early career fellowship with financial contributions made by the National Centre for Atmospheric Science and the British Geological Survey. D.J.L acknowledges Research Councils UK for the award of an RCUK fellowship and the Leverhulme Trust for the award of a Phillip Leverhulme Prize.

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TABLE CAPTIONS

Table 1: Showing the age range of the ten discrete minima in RMS error between 2.95 and 3.35 Ma BP, the best-fit (closest match to modern insolation distribution at the top of the atmosphere) solution within each of the RMS minima, the difference in global insolation (ΔINS) at the top of the atmosphere at each best-fit solution compared with modern, the root-mean-square deviation (RMS), the correlation coefficient (CC) and the standard deviation (SD) from modern for each time point and an assessment of how well each discrete RMS minima matches the established criteria for the selection of the Pliocene time slice (see Section 2.2). The discrete RMS minima highlighted in bold is encompassed by the selected interval time slice reconstruction.

Table 2: The orbital parameters of eccentricity, precession and obliquity for modern and the Pliocene time slice (3.205 Ma BP) according to the astronomical solution of Laskar et al. (2004).

Table 3: Preliminary list of sites included in the exiting PRISM time slab SST data set capable of providing SSTs to support the new time slice reconstruction (see Figure 6a).

Table 4: Preliminary list of terrestrial sites included in the PRISM time slab data set (Salzmann et al., 2008) *potentially* capable of providing vegetation data to support the new time slice reconstruction (see Figure 6b).

FIGURE CAPTIONS

Figure 1: Schematic representation of the PRISM methodology of Warm Peak Averaging adapted from Dowsett and Poore (1991). Idealised down core variation in sea surface temperature (SST) shown. Warm peak mean, warm peak minimum and warm peak maximum SST values are labelled along with minimum and mean SSTs during the interval. Communality cut-off highlighted, with peaks having a communality value of less than 0.7 being discarded (indicated by the cross).

Figure 2: Position of the first Pliocene time slice (thin red line) and the PRISM time slab (grey shaded band), relative to the geomagnetic polarity, magnetic reversals (black and white boxes), oxygen isotope stratigraphy (LR04 stack), planktic foraminiferal zones and calcareous nannofossil zones.

Figure 3: Comparison of insolation at 65° N on the 21st of June between the La93 versus La04 orbital solutions between 2.95 and 3.35 Ma BP.

Figure 4: Showing (a) the Lisiecki and Raymo (2005) benthic oxygen isotope stack, (b) obliquity with dashed horizontal line showing the present-day value, (c) precession and eccentricity as derived from the astronomical solution of Laskar et al. (2004; La04), with horizontal dashed black and solid red lines showing present-day values for Eccentricity and Precession, (d) the calculated root-mean-square error (RMS; Wm^{-2}) and (e) correlation coefficient (0-1) for orbital solution considered for the Pliocene time slice, and (f) the variation in global mean TOA insolation according to La04. The dashed horizontal green line in panel f denotes the modern value of global mean insolation. The vertical solid lines

through each panel represent the best-fit solutions considered in the study (black) and the discrete minima in RMS error identified as the Pliocene time slice time slice (solid red).

Figure 5: Insolation distribution at the top of the atmosphere (TOA) in Wm^{-2} for (a) the modern and the insolation anomaly between modern and (b) 3060 ka and (c) 3205 ka (derived from the La04 astronomical solution). 3060 ka is a time point during the PRISM time slab which exhibits the largest negative excursion in the benthic oxygen isotope record (Lisiecki and Raymo, 2005; Figure. 4). 3205 ka is the time point identified in this study that satisfies the outlined criteria for being chosen as the Pliocene time slice.

Figure 6: (a) Distribution of PRISM marine sites (circles) and locations of potential time slice SST data (triangles). The existing PRISM time slab reconstruction (PRISM3D) is confined to a time slab with duration 240 ka while the SST data set currently in development (PRISM4) represents a significant development toward a time slice centred on MIS KM5c (KM5.3) (b) Distribution of PRISM3D terrestrial palaeobotanical sites (circles) and locations of *potential* time slice vegetation data (triangles).

Figure 7: A compilation of published records of sea-surface temperature which span the Late Pliocene and encompass the time slice study proposed here. All SST data are from IODP sites. The red line corresponds to the ideal target identified by the orbital forcing comparison (Figure 5). The dark grey shading highlights a broader time window within which SST estimates could be derived, and in all probability, still reflect conditions during the time slice itself (a *Zone of Tolerance*). The light grey shading highlights an interval for study to help identify the time slice in marine records, and also to understand climate variability before and after the time slice (a *Zone of Investigation*). SST records (°C) are compared to a) the benthic

$\delta^{18}O$ stack, LR04 (Lisiecki and Raymo, 2005) and b) the deep-water temperature reconstruction from the North Atlantic site 607 (Sosdian and Rosenthal, 2009). c) 662, Atlantic (Herbert et al., 2010); d) 722, Arabian Sea (Herbert et al., 2010); e) 763, Indian Ocean (Karas et al., 2011); f) 214, Indian Ocean (Karas et al., 2009); g) 806, West Pacific (Wara et al., 2005); h) 846, East Pacific (Herbert et al., 2010); i) 847, East Pacific (Wara et al., 2005); j) 847, East Pacific (Dekens et al., 2007); k) 1082, South east Atlantic (Etourneau et al., 2009); l) 882, North west Pacific 882 (Martinez-Garcia et al., 2010); m) 982, North Atlantic (Lawrence et al., 2009); n) 607, North Atlantic (Lawrence et al., 2011); o) 1090, Southern Ocean (Martinez-Garcia et al., 2010).

Figure 8: Annual mean and seasonal mean (December, January and February – DJF and June, July and August - JJA) Pliocene Surface Air Temperature predictions from HadCM3: (top) identified time slice minus a Pliocene experiment with a modern orbital configuration (PRISM3D); (middle) Pliocene experiments given orbital configurations appropriate to 3195 and 3215 ka BP (3195 and 3215 ka minus 3205 ka BP); (bottom) an experiment for the MIS K1 PlioMAX *super interglacial* event minus the identified time slice at 3205 ka BP characterised by a near modern orbital configuration.

Tables

Table 1: Showing the age range of the ten discrete minima in RMS error between 2.95 and 3.35 Ma BP, the best-fit (closest match to modern insolation distribution at the top of the atmosphere) solution within each of the RMS minima, the difference in global insolation (ΔINS) at the top of the atmosphere at each best-fit solution compared with modern, the root-mean-square deviation (RMS), the correlation coefficient (CC) and the standard deviation (SD) from modern for each time point and an assessment of how well each discrete RMS minima matches the established criteria for the selection of the Pliocene time slice (see Section 2.2). The discrete RMS minima highlighted in bold is encompassed by the selected interval time slice reconstruction.

RMS Minima (RMS < 5 Wm^{-2})	Age Range ka	Best-fit Time Point (ka)	ΔINS Wm^{-2}	RMS Wm^{-2}	CC (0 to 1)	SD Wm^{-2}	Description
1	3002-3004	3003	0.0532	4.1162	0.9997	158.4268	Not situated at or near a discrete negative peak in LR04 stack
2	3118-3121	3119	0.0433	3.4920	0.9998	185.4160	Not situated at or near a discrete negative peak in LR04 stack, but just above the base of the Kaena reversal (3116 ka;) in the Gauss Normality Chron (C2An.2n; Gradstein et al., 2004)
3	3185-3186	3185	0.0606	4.6702	0.9996	158.3028	Situated on a descending (towards positive) limb between two negative peaks
4	**3204-3207**	**3205**	**-0.0218**	**4.2657**	**0.9996**	**158.1467**	**Centred on a broad peak (negative excursion), with Mammoth reversal (C2An.2r) directly before (3207 ka; Gradstein et al., 2004)**
5	3219	3219	-0.0204	4.9019	0.9995	158.0499	Within an isotopically light period, but on the falling limb with values becoming less negative
6	3236-3240	3238	0.0118	1.4689	1.0000	158.2245	In the transition zone towards a negative peak
7	3258-3260	3259	0.0296	2.9629	0.9998	158.1762	Not situated at or near a discrete negative peak in LR04 stack
8	3276-3280	3278	-0.0070	1.1293	1.0000	158.2666	Not situated at or near a discrete negative peak in LR04 stack
9	3293-3296	3295	-0.0014	1.4502	1.000	158.0723	Situated at peak in positive isotopic excursion (M2 event)
10	3114	3314	0.0641	4.7294	0.9996	158.3965	Outside of PRISM time slab and on a trend towards more positive isotope values

Table 2: The orbital parameters of eccentricity, precession and obliquity for modern and the Pliocene time slice (3.205 Ma BP) according to the astronomical solution of Laskar et al. (2004).

Time point	Eccentricity	Precession	Obliquity
Modern	0.016702	0.016280	23.4393°
3205 ka	0.007483	0.006048	23.4736°

Table 3: Preliminary list of sites included in the exiting PRISM time slab SST data set capable of providing SSTs to support the new time slice reconstruction (see Figure 6a).

Core Site	Lat. (°N)	Long. (°E)
DSDP 552	56.04	-23.23
DSDP 594	-45.52	174.95
DSDP 607	41.00	-32.96
DSDP 610	53.22	-18.89
ODP 658	20.75	-18.58
ODP 659	18.08	-21.03
ODP 662	-1.39	-11.74
ODP 704	-46.88	7.42
ODP 722	16.62	59.80
ODP 758	5.38	90.37
ODP 846	-3.09	-90.82
ODP 849	0.18	-110.52
ODP 925	4.20	-43.49
ODP 926	3.72	-42.91
ODP 927	5.47	-44.48
ODP 928	5.46	-43.75
ODP 929	5.98	-43.74
ODP 982	57.52	-15.87
ODP 999	12.74	-78.74
ODP 1085	-29.37	13.99
ODP 1092	-46.41	7.08
ODP 1125	-42.55	-178.17
ODP 1143	9.36	113.29
ODP 1148	18.84	116.57
ODP 1207	37.79	162.75
ODP 1208	36.13	158.20
ODP 1209	32.65	158.51
ODP 1210	32.22	158.26
ODP 1211	32.00	157.85
IODP U1313	41.00	-32.96

Table 4: Preliminary list of terrestrial sites included in the PRISM time slab data set (Salzmann et al., 2008) *potentially* capable of providing vegetation data to support the new time slice reconstruction (see Figure 6b).

Map ID	Site	Lat. (°N)	Long. (°E)
1	ODP 646, Labrador Sea	58.22	-48.20
2	ODP 646, Leg 105	58.21	-48.37
3	Great Salt Lake, Utah	41.00	-112.50
4	DSDP 467, Leg 63	33.85	-120.76
5	ODP 642, Norwegian Sea	67.22	2.94
6	La Londe, Normandy	49.31	0.95
7	Alpes-Maritimes	43.82	7.19
8	DSDP 380, LEG 42B	42.10	29.61
9	Rio Maior	39.35	-8.93
10	Andalucia G1	36.38	-4.75
11	Tarragona	40.83	1.13
12	Bianco/Bovalino	38.25	16.40
13	Hula Basin	33.00	35.60
14	Nador	35.18	-2.93
15	ODP 658, Cape Blanc	20.75	-18.58
16	Hadar	11.29	40.63
17	DSDP 231, Leg 24	11.89	48.25
18	DSDP 532, Leg 75	-21.09	14.46
19	ODP 1082	-21.10	11.82
20	Yumen, Jiuxi Basin	39.78	97.53
21	Xifeng, Loess Plateau	35.88	107.97
22	Himi Area, Toyama	37.15	137.25
23	ODP 794A	40.19	138.22
24	DSDP 440B / 438A	40.00	143.60
25	Yallalie, Perth	-30.43	115.77
26	ODP 1123, Leg 181	-41.78	-171.50

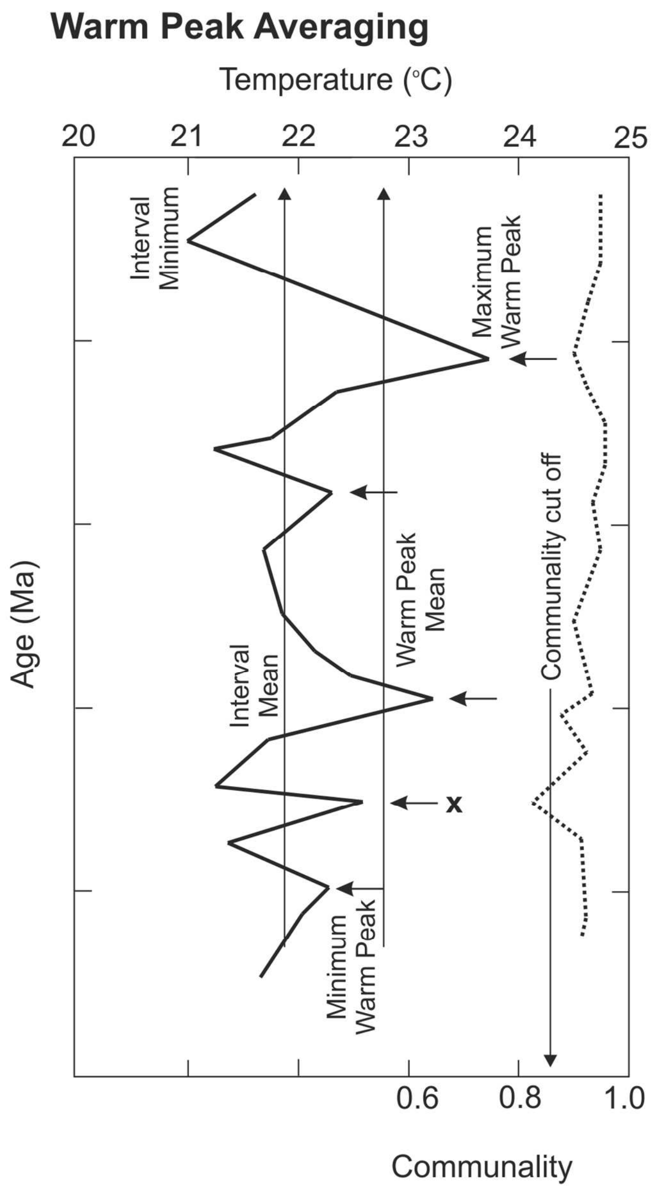

Figure 1: Schematic representation of the PRISM methodology of Warm Peak Averaging adapted from Dowsett and Poore (1991). Idealised down core variation in sea surface temperature (SST) shown. Warm peak mean, warm peak minimum and warm peak maximum SST values are labelled along with minimum and mean SSTs during the interval. Communality cut-off highlighted, with peaks having a communality value of less than 0.7 being discarded (indicated by the cross).

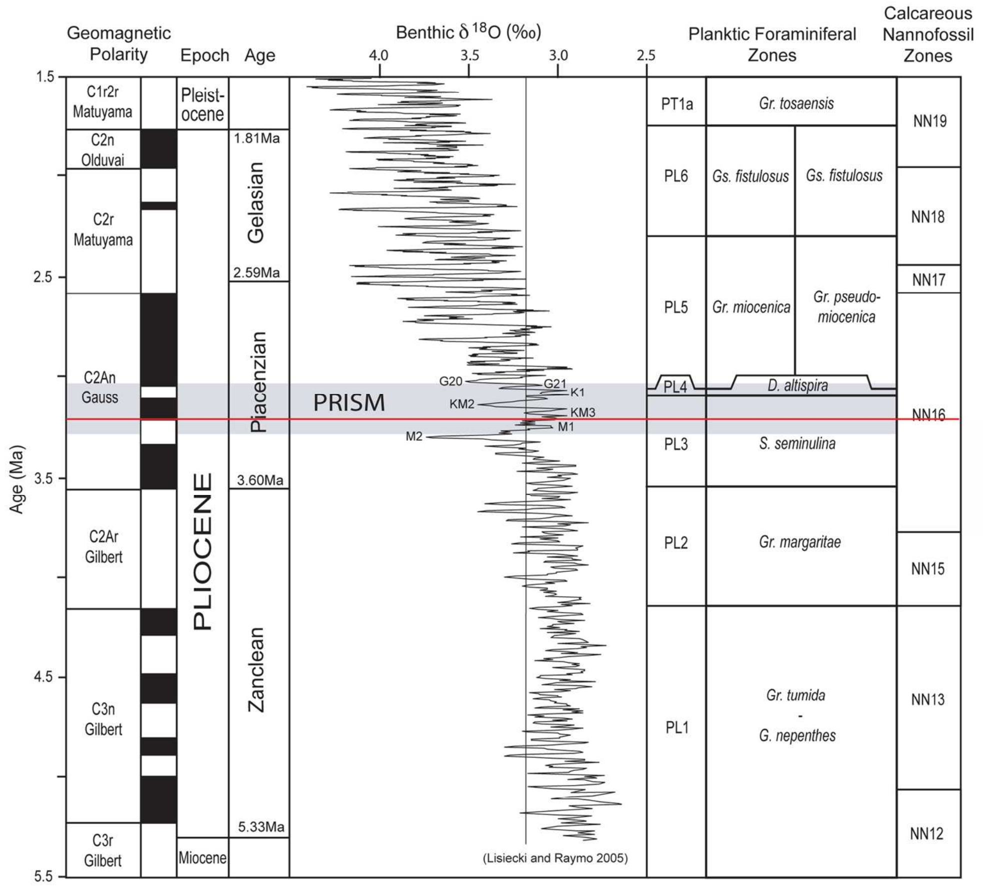

Figure 2: Position of the first Pliocene time slice (thin red line) and the PRISM time slab (grey shaded band), relative to the geomagnetic polarity, magnetic reversals (black and white boxes), oxygen isotope stratigraphy (LR04 stack), planktic foraminiferal zones and calcareous nannofossil zones.

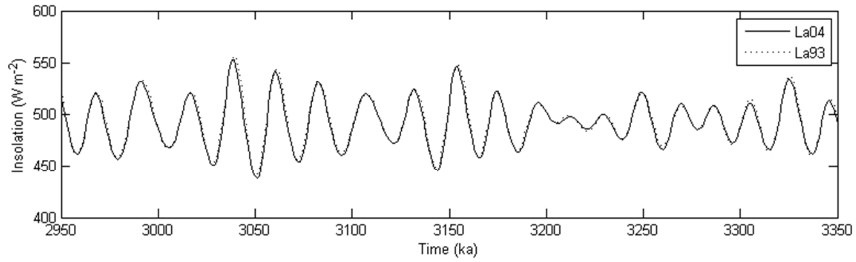

Figure 3: Comparison of insolation at 65° N on the 21st of June between the La93 versus La04 orbital solutions between 2.95 and 3.35 Ma BP.

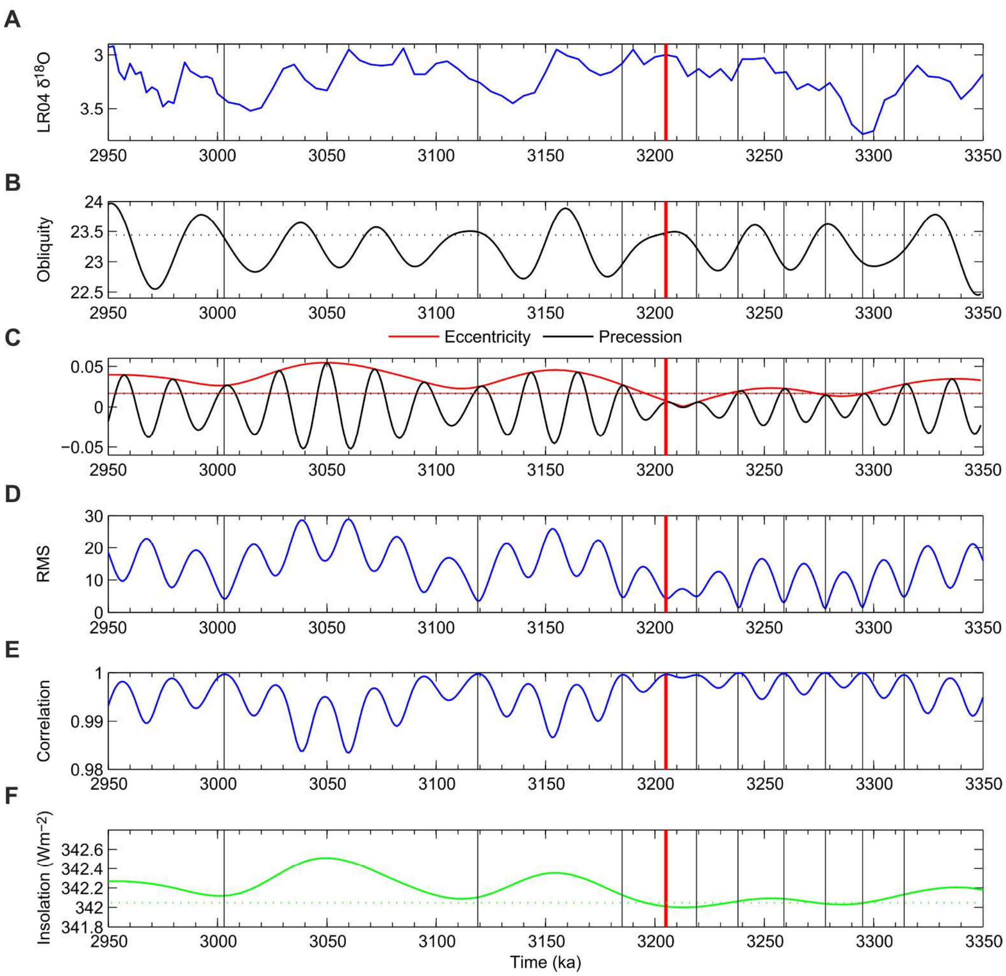

Figure 4: Showing (a) the Lisiecki and Raymo (2005) benthic oxygen isotope stack, (b) obliquity with dashed horizontal line showing the present-day value, (c) precession and eccentricity as derived from the astronomical solution of Laskar et al. (2004; La04), with horizontal dashed black and solid red lines showing present-day values for Eccentricity and Precession, (d) the calculated root-mean-square error (RMS; Wm$_{-2}$) and (e) correlation coefficient (0-1) for orbital solution considered for the Pliocene time slice, and (f) the variation in global mean TOA insolation according to La04. The dashed horizontal green line in panel f denotes the modern value of global mean insolation. The vertical solid lines through each panel represent the best-fit solutions considered in the study (black) and the discrete minima in RMS error identified as the Pliocene time slice time slice (solid red).

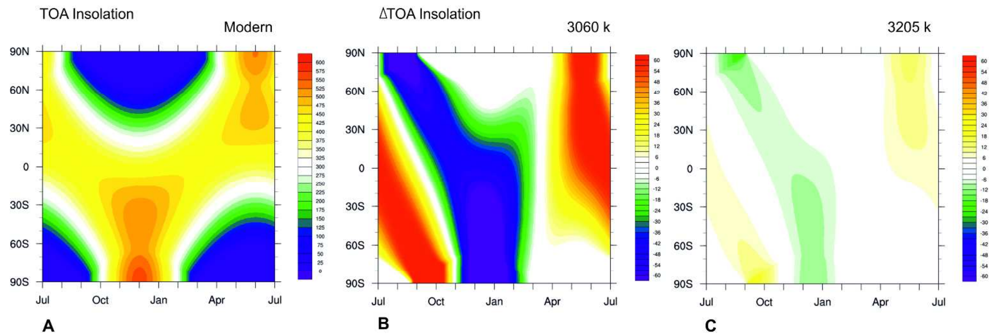

Figure 5: Insolation distribution at the top of the atmosphere (TOA) in Wm^{-2} for (a) the modern and the insolation anomaly between modern and (b) 3060 ka and (c) 3205 ka (derived from the La04 astronomical solution). 3060 ka is a time point during the PRISM time slab which exhibits the largest negative excursion in the benthic oxygen isotope record (Lisiecki and Raymo, 2005; Figure. 4). 3205 ka is the time point identified in this study that satisfies the outlined criteria for being chosen as the Pliocene time slice.
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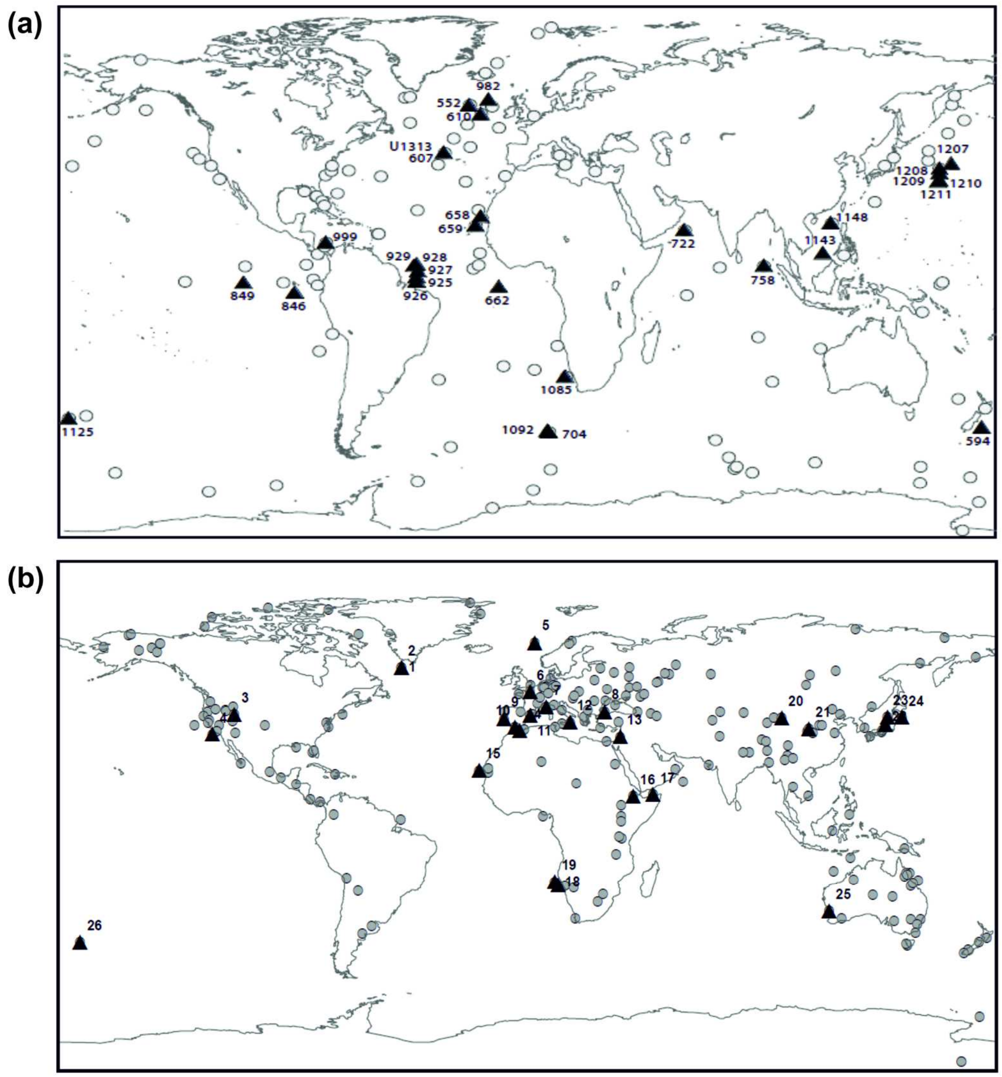

Figure 6: (a) Distribution of PRISM marine sites (circles) and locations of potential time slice SST data (triangles). The existing PRISM time slab reconstruction (PRISM3D) is confined to a time slab with duration 240 ka while the SST data set currently in development (PRISM4) represents a significant development toward a time slice centred on MIS KM5c (KM5.3) (b) Distribution of PRISM3D terrestrial palaeobotanical sites (circles) and locations of potential time slice vegetation data (triangles).
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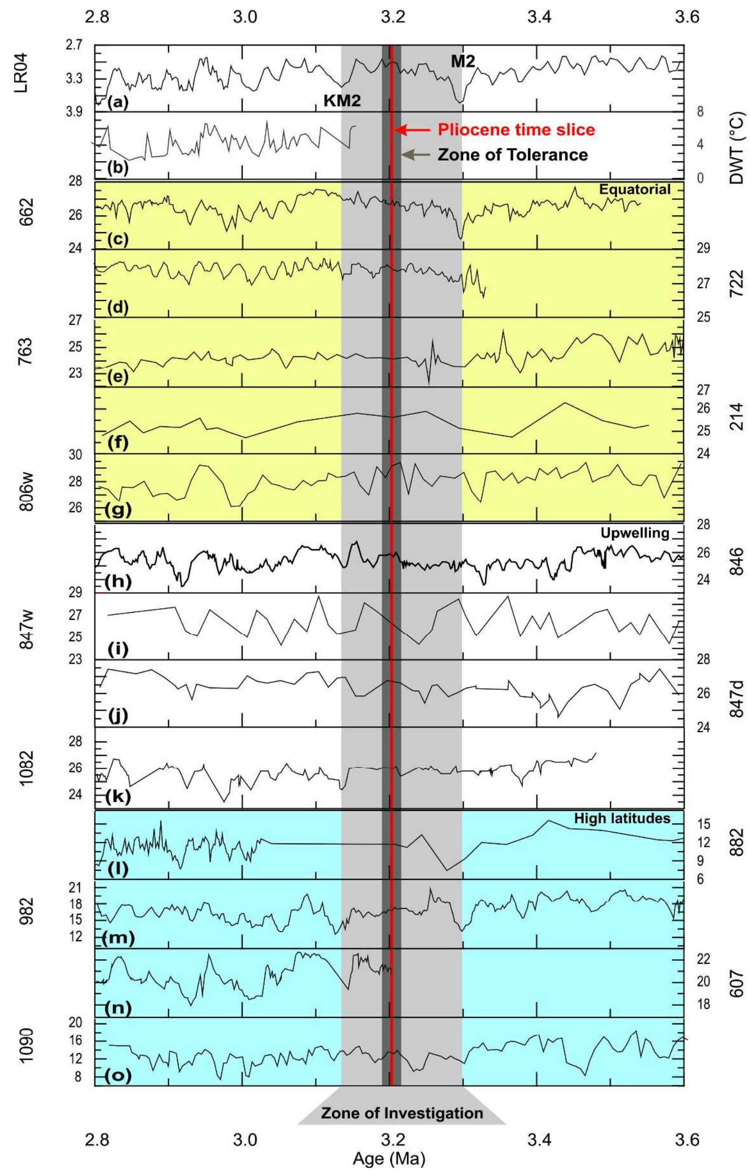

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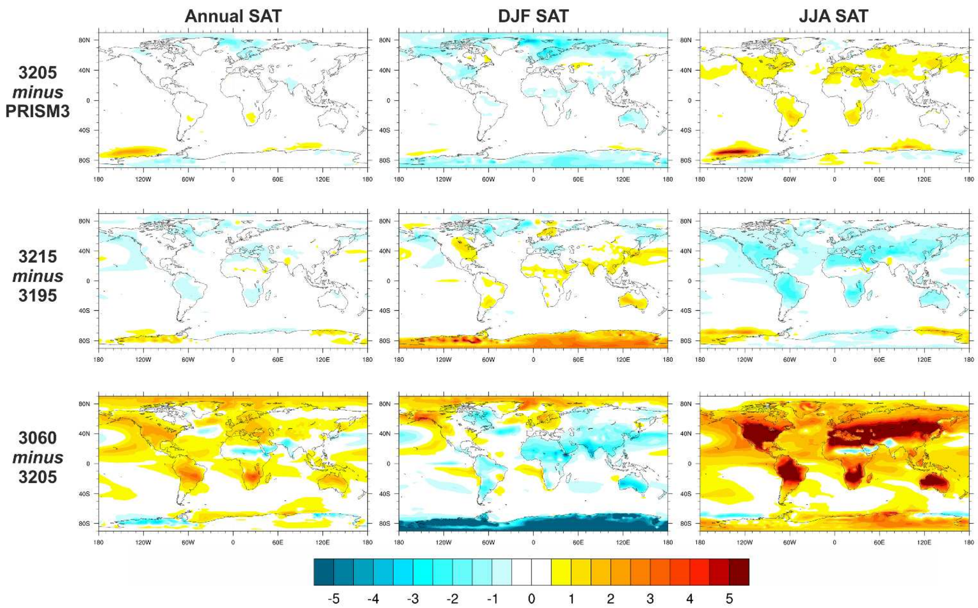
et al., 2009); n) 607, North Atlantic (Lawrence et al., 2011); o) 1090, Southern Ocean (Martinez-Garcia et al., 2010).
176x289mm (300 x 300 DPI)



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