Introduction. Pliocene climate, processes and problems

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Climate predictions produced by numerical climate models, often referred to as general circulation models (GCMs), suggest that by the end of the twenty-first century global mean annual surface air temperatures will increase by 1.1–6.4°C. Trace gas records from ice cores indicate that atmospheric concentrations of CO2 are already higher than at any time during the last 650 000 years. In the next 50 years, atmospheric CO2 concentrations are expected to reach a level not encountered since an epoch of time known as the Pliocene. Uniformitarianism is a key principle of geological science, but can the past also be a guide to the future? To what extent does an examination of the Pliocene geological record enable us to successfully understand and interpret this guide? How reliable are the ‘retrodictions’ of Pliocene climates produced by GCMs and what does this tell us about the accuracy of model predictions for the future? These questions provide the scientific rationale for this Theme Issue.

Keywords: Pliocene; uniformitarianism; proxies; general circulation models, climate

1. The Pliocene epoch

The Pliocene epoch (Plio more, Cene recent) represents the uppermost subdivision of the Tertiary Period. It spans a time frame from ca 5.3 to 1.8 Myr BP, according to the geological time scale of Gradstein et al. (2004). The epoch incorporates the time interval in which the Earth experienced a transition from relatively warm climates to the prevailing cooler climates of the Pleistocene (Dowsett & Poore 1991; Mudelsee & Raymo 2005; Raymo et al. 2006; Lisieski & Raymo 2007).

Climatically, the Pliocene can be crudely divided into three phases, (i) an Early Pliocene warm period, (ii) a relatively short-lived ‘warm blip’ centred ca 3 Myr BP referred to as the Mid-Pliocene warm interval, and (iii) a climatic deterioration

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during the Late Pliocene leading to the high-magnitude climate variability associated with Pleistocene glacial/interglacial cycles (figure 1). Available higher-resolution climate records for the Pliocene (e.g. Leroy & Dupont 1994; Lawrence et al. 2006) suggest that even relatively short subdivisions of the epoch were characterized by variations in precipitation and temperature, occurring on the time scale of several thousand years. This climatic variability is only partially resolved

Figure 1. Pliocene magnetostratigraphic framework, after Berggren et al. (1995). Benthic δ¹⁸O record from Lisiecki & Raymo (2005). Vertical line through isotope curve represents present-day value.

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in terms of magnitude (Haywood et al. 2002a; Draut et al. 2003) but often occurred with detectable periodicities of 41 000 and 19 000, 21 000 and 23 000 years linked to obliquity and precessional cycles (e.g. Draut et al. 2003; Becker et al. 2006; Sprovieri et al. 2006).

Even though a progressive cooling occurred during the Tertiary, the Pliocene world appears to have been, on average, warmer than present day (Jansen et al. 2007). The ancient distribution of planktonic foraminifera along with terrestrial fossil fauna and flora indicates that winter and summer temperatures in the mid-latitudes were often several degrees higher than present (e.g. Thompson 1991; Dowsett et al. 1996; Thompson & Fleming 1996; Salzmann et al. 2009). The greatest warming appears to have been in the high latitudes where temperatures were often elevated enough to allow species of animals and plants to exist at higher latitudes than their nearest modern relatives (Adam 1994; Francis & Hill 1996; Ashworth & Kuschel 2003; Ashworth & Preece 2003; Ashworth & Thompson 2003; Ashworth & Cantrill 2004; Ballantyne et al. 2006; Francis et al. 2007; Salzmann et al. 2009). Realization that significant warming took place at high latitudes has potentially important ramifications for the behaviour and extent of Pliocene sea ice, ice sheets and sea level (Dwyer & Chandler 2009; Lunt et al. 2009; Naish & Wilson 2009).

2. The past is a guide to the future?

Uniformitarianism, the observation that fundamentally the same geological processes that operate today also operated in the distant past, is a key principle of modern geology. The methodological significance of the principle is summarized in the statement: ‘The present is the key to the past.’ Uniformitarianism originated with the work of the geologist James Hutton but was refined by John Playfair and popularized by Charles Lyell’s Principles of geology (1830), but can the principle be reversed and extended so that the past becomes the key to future?

The search for geological analogues for future climate change is not new, but what is new is a realization that, given current and projected levels of greenhouse gases (GHGs) in the atmosphere, we must travel far into the geological past to find intervals of time in which GHGs, as well as global temperatures, were comparable to what we predict will occur by the end of the twenty-first century. Trace gas records from ice cores indicate that atmospheric concentrations of CO₂ are already higher than at any time during the last 650 000 years, discounting any period within that time as an analogue for late twenty-first century climate (Siegenthaler et al. 2005).

Palaeoclimatology, therefore, faces a dilemma. The majority of scientific effort has been, and remains, devoted to understanding (i) glacial and interglacial climate variability during the Pleistocene, (ii) Holocene climate variability, and (iii) the instrumental/historical record of climate change spanning the last 2000 years. For these periods our palaeoenvironmental datasets, and therefore our state of knowledge, are at their best, yet no interval occurring during the last 650 000 years is extreme enough to be an indicator of late twenty-first century climate. Indeed, for most of the last 650 000 years, climate has been very much colder than today. So in terms of the relevance of palaeoclimate studies to understanding and
predicting future climate change, has an emphasis on studying the Quaternary left palaeoclimatology in a weak position? Quaternary palaeoclimate studies have provided us with a unique opportunity to examine rapid high-magnitude climate changes as well as given us the chance to test the robustness of climate models in simulating dramatically different climate states; at the same time our knowledge of warm climate intervals during the Tertiary has also grown significantly.

Estimates of atmospheric CO₂ levels during the Pliocene have been derived through analyses of the stomatal density of fossil leaves (e.g. Van der Burgh et al. 1993; Kürschner et al. 1996) and through analyses of δ¹³C ratios of marine organic carbon (Raymo & Rau 1992; Raymo et al. 1996). Both techniques indicate that absolute CO₂ levels during the warmest intervals of time, while variable, may have been as high as 425 ppm by volume (Raymo et al. 1996), meaning that the warmest intervals of the Pliocene may represent an equilibrium climate response to atmospheric CO₂ levels that will be attained approximately by the middle of the twenty-first century.

The increasing importance of the Pliocene in the context of future climate change is highlighted by the epoch’s inclusion in the recent IPCC fourth assessment report, which, focusing on a particular interval of the Pliocene, states that,

the mid-Pliocene is the most recent interval of geological time when mean global temperatures were substantially warmer for a sustained period; ~2 °C to 3 °C above pre-industrial temperatures. Therefore, the mid-Pliocene represents an accessible example of a world that is similar in many respects to what models estimate could be the Earth of the late twenty-first century. The mid-Pliocene is recent enough that the continents and ocean basins had nearly reached their present geographic configuration. Taken together, the average of the warmest times during the mid-Pliocene presents a view of the equilibrium state of a globally warmer world, in which atmospheric CO₂ concentrations were likely higher than pre-industrial values.

(Jansen et al. 2007, ch. 6, pp. 440–442)

3. Climate processes and problems

Given that the Pliocene has now entered the political mainstream of climate change science, we are fortunate to have a large body of existing work to refer to and to use as the foundation for future scientific study. Decades of painstaking research by individuals and small groups of scientists in a number of different countries, working in a scientific area that was, until very recently, considered by many to be marginal, have provided ever more detailed reconstructions of what Pliocene environments and climates were like, and what climate processes may have been responsible for the initiation, sustenance and termination of Pliocene warm periods.

The work of the United States Geological Survey’s PRISM Group (Pliocene Research Interpretation and Synoptic Mapping) in documenting Mid-Pliocene environmental conditions around the world is a case in point. Twenty years of detailed palaeoenvironmental reconstruction, using various proxies such as planktonic foraminifera, diatoms, ostracods, pollen and leaves, has culminated in the release of the PRISM 3D 2° × 2° digital dataset (Dowsett 2007). PRISM 3D provides information on global Mid-Pliocene sea surface temperatures (SSTs) and
Atlantic/Pacific Ocean bottom water temperatures, vegetation cover, terrestrial and sea ice cover, sea levels and topography specifically designed for integration into general circulation models (GCMs) and/or as a means to evaluate outputs from Pliocene climate modelling studies. As such, PRISM 3D represents the most detailed palaeoenvironmental reconstruction available for any geological time period older than the last glacial (see http://geology.er.usgs.gov/eespteam/prism/prism3main.html for further details). This and earlier versions of the PRISM dataset have facilitated a number of modelling exercises designed to examine the dynamics of Mid-Pliocene climates (e.g. Chandler et al. 1994; Sloan et al. 1996; Haywood et al. 2000a, b; Jiang et al. 2005; Haywood & Valdes 2006).

The climatic drivers behind warm intervals of the Pliocene have been widely discussed (e.g. Raymo et al. 1996) and can be crudely summarized as relating to: (i) palaeogeographic change, e.g. altered elevations of major mountain chains such as the western cordillera of North and South America (Rind & Chandler 1991); (ii) altered atmospheric trace gas concentrations and water vapour content (e.g. Raymo & Rau 1992; Van der Burgh et al. 1993); (iii) changes to ocean circulation (Ravelo & Andresson 2000; Cane & Molnar 2001), ocean heat transport (e.g. Dowsett et al. 1992; Haug & Tiedemann 1998; Kim & Crowley 2000; Lunt et al. 2008a), or the thermal structure of the oceans (e.g. Philander & Fedorov 2003; Wara et al. 2005; Fedorov et al. 2006); and (iv) feedbacks generated through altered land cover (including ice sheet extent), surface albedo, cloud cover and temperature (Haywood & Valdes 2004, 2006; Salzmann et al. 2008, 2009).

Many previous studies have centred on the role of the atmosphere and oceans (Raymo et al. 1996). As previously stated, specific proxies for atmospheric CO₂ have identified elevated concentrations during warm intervals of the Pliocene. The CO₂ increases reconstructed for the Pliocene, up to 425 ppm by volume, would produce a radiative forcing of approximately 2.5 W m⁻². This may be sufficient to explain the warmth of the Pliocene globally (depending on the chosen climate sensitivity parameter, and whether there are any significant changes in other aspects of the radiative forcing), but it has not been able on its own to explain the regional changes in surface temperature suggested by palaeoclimate proxies (Crowley 1996). Therefore, additional mechanisms working independently or combined with variations in CO₂ concentrations in the atmosphere are required to drive and maintain the warmer Pliocene conditions.

An alternative explanation invokes a change in the heat transport of the oceans. SST estimates from diatom and planktonic foraminiferal assemblages, synthesized as part of the PRISM project, originally showed no warming relative to present in the tropics but significant warming at higher latitudes, especially in the North Atlantic and Pacific oceans (Dowsett et al. 1996, 1999, 2009, see figure 2). This pattern is indicative of enhanced meridional ocean heat transport, which may have been a direct result of more vigorous North Atlantic Deep Water (NADW) formation and thermohaline circulation (THC) during certain intervals of the Pliocene compared with present day (Dowsett et al. 1996, 1999; Raymo et al. 1996). Therefore, investigation of this period may provide critical information regarding the nature and behaviour of NADW formation and THC under conditions of greater global warmth that have characterized the recent geological past, and may characterize the near future (Dowsett et al. 2009).
Although the possibility of enhanced meridional ocean heat transport was highlighted in early modelling studies (Rind & Chandler 1991), many difficulties and unexplained issues remain. Paradoxically, a reduced latitudinal SST gradient implies weaker atmospheric forcing of surface oceanic circulation, and hence weaker oceanic heat transport from Equator to higher latitudes (Crowley 1996). This is a common problem associated with the dynamics of past warm

Figure 2. PRISM SST anomalies for (a) February and (b) August. Anomalies derived by subtracting present-day SST (Reynolds & Smith 1995) from PRISM2 SST (Dowsett et al. 1999).
climates (Valdes 2000). Problems exist in any explanation of Pliocene warmth that is based solely upon strengthening of the THC as it is difficult (i) to ascribe a thermohaline coupling argument to all ocean basins and (ii) to generate the correct reconstructed hemispheric temperature distribution (Crowley 1996; Valdes 2000). However, it is clear that such an argument is too simplistic, as climate processes operating at the regional scale are capable of overriding global-scale trends (Haywood et al. 2000a).

To test these and other ideas Haywood & Valdes (2004), using the HadCM3 GCM, carried out the first fully coupled ocean–atmosphere GCM simulation for the Mid-Pliocene. The simulation resulted in a global surface temperature warming of 3°C compared with present day. In contrast to earlier modelling studies (e.g. Chandler et al. 1994; Sloan et al. 1996; Haywood et al. 2000a,b), which have used prescribed PRISM SSTs, surface temperatures increased in most areas, including the tropics. Compared with a pre-industrial simulation, the model predicted a general pattern of ocean warming in both hemispheres to a depth of 2000 m, below which no significant differences were noted. Sea ice coverage was massively reduced and the velocity of the Gulf Stream/North Atlantic Drift was greater in the Pliocene simulation.

Analysis of the model-predicted ocean overturning suggested a global pattern of reduced outflow of Antarctic bottom water, a shallower depth for NADW formation and weaker THC. Model diagnostics for heat transport indicated that neither the oceans nor the atmosphere transported significantly more heat in the Mid-Pliocene case. Rather, the results indicated that the major contributing mechanism to Mid-Pliocene warmth was the prescribed reduced extent of high-latitude terrestrial ice sheets and sea ice cover, resulting in a strong ice–albedo feedback (Haywood & Valdes 2004).

The results from this modelling study conflict with two well-established interpretations of Pliocene ocean conditions based on proxy data, which indicate that tropical SSTs did not increase, and that warmer mid-latitude SSTs were caused by enhanced meridional ocean heat transport/THC. So, are Pliocene ocean data telling us that this model is wrong? This has yet to be determined. A later study of tropical and low-latitude SSTs (Haywood et al. 2005) using alkenone palaeothermometry indicated that SST warming in tropical upwelling systems was at least possible during the Pliocene. Recent multi-proxy studies of equatorial Pacific SST show that the east–west gradient was greatly reduced during the Mid-Pliocene due to undeniable warming of the eastern equatorial Pacific (EEP) and relative stability of the western equatorial Pacific warm pool (Wara et al. 2005; Ravelo et al. 2006; Dowsett & Robinson 2009). Geochemical data suggest modest warming in the west. While faunal-based methods, difficult to apply in the west where present-day SST is at the limit of the calibration data (approx. 30°C), hint at the possibility of short periods within the Mid-Pliocene where SST was higher than 30°C (Dowsett & Robinson 2009). Resolution of the Pliocene tropical SST debate is vital if we are to deconvolve the role of atmosphere and oceans, and the carbon cycle in general, in Pliocene warmth and test the efficacy of outputs from Pliocene ocean–atmosphere GCM studies.

The role of, and feedbacks related to, the cryosphere are likely to be central to any explanation of Pliocene warmth. Unfortunately, our knowledge and ability to reconstruct the Pliocene cryosphere is incomplete and limited. Proximal geological records from the Antarctic and Greenland are few and far between, yet
they provide the best opportunity to reconstruct ice sheet behaviour during the Pliocene. The value of international projects that aim to study high-latitude palaeoceanography via the collection of marine sediment cores is highlighted by the success of the recent ACEX expedition to the Arctic (IODP Leg 302, see Pagani et al. (2006) and Jakobsson et al. (2007)) and the current ANDRILL project (Antarctic Drilling in McMurdo Sound), which has recovered a thick sequence of marine deposits from underneath the Ross Ice Shelf providing a unique window on ice shelf stability during Pliocene warm intervals. New approaches in reconstructing Neogene ice sheet behaviour on land are also yielding exciting results. For example, the study of Neogene ice–volcano interactions on the Antarctic Peninsula and North Victoria Land is providing a new way to examine the presence–absence of ice during the Neogene and providing critical estimates of ice thickness (e.g. Smellie et al. 2006).

Indications of Pliocene ice sheet behaviour are available from distal sources via oxygen isotope ratios of benthic foraminifera and ostracods combined with Mg/Ca ratios (e.g. Lear et al. 2000; Dwyer & Chandler 2009; Naish & Wilson 2009). However, currently these combined benthic O\(^{18}\) and Mg/Ca records are sparse and do not provide any information on how the ice was geographically distributed. This situation must be remedied before an assessment of the reproducibility of these distal geochemical records of global ice volume is possible (Dwyer & Chandler 2009; Naish & Wilson 2009).

Traditionally, reconstructions of Pliocene ice sheets have been based solely upon past sea-level estimates, derived from well-dated palaeo-shorelines (Dowsett & Cronin 1990; Wardlaw & Quinn 1991), but which may have significant uncertainties associated with the estimates. Owing to these uncertainties, estimates of the Mid-Pliocene Antarctic ice sheet volume, for example, range from near present-day values to greater than 33 per cent reduction compared with modern. This uncertainty severely hampers modelling efforts designed to investigate the cause of Pliocene warmth and restricts the value of this period as a test-bed for numerical climate models. Therefore, refined sea-level records with reduced uncertainties are urgently required (e.g. Dwyer & Chandler 2009; Naish & Wilson 2009).

As geological evidence for the size and extent of Pliocene ice sheets and ice sheet variation is currently inconclusive, it is important that the plausible extent of the ice sheets during the Pliocene is assessed through coupled climate and ice sheet modelling exercises. Outputs from Pliocene GCM modelling experiments are currently being used to drive three-dimensional, thermomechanical ice sheet models (Hill et al. 2007; Lunt et al. 2008a,b, 2009), which will enable us to estimate the plausible state of the ice sheets during warm climate intervals in the Pliocene.

4. Recent developments and future challenges

One of the most exciting recent developments in Pliocene research has been the examination of tropical climate dynamics and tropical high-latitude climate linkages. Recent palaeoceanographic studies that have reconstructed SST gradients across the tropical Pacific, using Mg/Ca and \(\delta^{18}O\) analyses of planktonic foraminifera, alkenone palaeothermometry and faunal methods, indicate that the SST gradient across the Pacific during the Early and Mid-
Pliocene was substantially lower than it is today (approx. 1.5°C compared with approx. 6°C for the modern; Wara et al. 2005; Dowsett & Robinson 2009). Mean SSTs in the EEP were considerably warmer than they are at present (by approx. 3°C). This scenario of warmer EEP SSTs and a reduced SST gradient across the tropical Pacific is akin to what occurs during a modern El Niño event, thus the Early and Mid-Pliocene have been characterized as exhibiting permanent El Niño-like conditions.

Barreiro et al. (2006) prescribed a permanent El Niño-like state in a GCM simulation for present day and found that, given such a condition, the trade winds along the Equator, and hence the Walker Circulation, collapse. Low-level stratus clouds in the low latitudes diminish, reducing the albedo of the planet and increasing global temperatures. The atmospheric concentration of water vapour also increases. Since water vapour is responsible for approximately 70 per cent of the known absorption of outgoing long-wave radiation, an increase in atmospheric water vapour provides a further contribution to global warming. Philander & Fedorov (2003) hypothesize that as surface temperatures warm in the future, due to the anthropogenic emissions of GHGs, the thermocline in the tropical Pacific may deepen, causing a reversion to a Pliocene permanent El Niño-like state. The authors argue that the transition from uniformly warm tropics to tropics with zonal SST gradients, ca 3 Myr ago, provided important positive feedbacks for the amplification of glacial cycles and the onset of Northern Hemisphere glaciation.

Haywood et al. (2007) and Lunt et al. (2008a) present two fully coupled ocean–atmosphere GCM simulations for the Pliocene in which the behaviour of the El Niño Southern Oscillation (ENSO) is examined. The first experiment (MidPlio\textsuperscript{Control}) was initialized with a full suite of Mid-Pliocene boundary conditions derived from the PRISM dataset. The second experiment (EarlyPlio\textsuperscript{Control}) was identical to experiment MidPlio\textsuperscript{Control}, except that the Central American Seaway was specified as being open, allowing a connection to be established between the western tropical Atlantic and eastern tropical Pacific oceans, as was the case during the Early Pliocene. In both experiments, statistical analyses of model-predicted Pacific SSTs, combined with the examination of 100 years of model-predicted December, January and February (DJF) surface air temperature variability for El Niño region 3.4 (central and eastern Pacific), reveal a pattern of ENSO variability in both experiments (figure 3). The standard deviation of DJF surface air temperatures in the central and eastern Pacific suggests that the variability of ENSO in experiment MidPlio\textsuperscript{Control} is, in fact, greater than that for the pre-industrial experiment. However, with a prescribed connection between the Atlantic and Pacific oceans through the Central American Seaway (EarlyPlio\textsuperscript{Control}), variability in surface air temperatures decreased, underlining the importance of performing further sensitivity experiments that explore the impact on ENSO behaviour of altered geological boundary conditions (Bonham et al. 2009).

Given the temporal resolution of the palaeoceanographic data used in this context, which is at best one sample spanning 10 000 years of actual time (Wara et al. 2005), it is clear that no record is capable of proving or disproving the existence of a permanent El Niño state during the Early or Mid-Pliocene, since ENSO events occur over decadal to sub-decadal time scales. Ideally, an approach capable of documenting SST variability at an annual or even sub-annual
resolution would be used (for example, stable isotope or Mg/Ca analysis of annual growth layers of mollusc shells or corals; Haywood et al. 2007). However, the data do provide snapshots of the mean state of tropical Pacific SSTs at specific geographical locations during the Pliocene, and it is entirely plausible that a fundamental shift in the behaviour of ENSO during the Pliocene would be reflected by a change in the mean state of SSTs in the EEP (Rickaby & Holloran 2005; Wara et al. 2005).

Molnar & Cane (2002) suggest that the pattern of temperature and precipitation change derived from regional proxy data during the Pliocene is, in many cases, similar to weather and climate patterns observed during a modern El Niño event, thus providing far-field evidence in support of a permanent El Niño state during the Pliocene. However, the far-field effects or signals of modern El Niño events can be very weak and, as is shown by Bonham et al. (2009), any apparent El Niño pattern in the proxy record can easily be explained by other changes in the Pliocene Earth system (such as altered terrestrial orography, global ice cover, global vegetation patterns and atmospheric trace gas concentrations), making it impossible to support El Niño as a ‘unique solution’ that explains most of the significant regional differences in Pliocene climate compared with present day.

Given the clear requirement to reconstruct and model Pliocene climates at high temporal resolutions, new approaches to proxy reconstruction must be adopted to provide the necessary data. One example of how the mean annual range of temperature (MART) for localities during the Pliocene can be estimated can be found in the inverse relationship between the size of cheilostome bryozoan zooids and water temperature. Williams et al. (2009) have used MART data from fossils collected from a range of latitudes to provide information about shelf SSTs.

Figure 3. One hundred years of DJF surface air temperature (°C) for El Niño region 3.4 (central and eastern tropical Pacific) predicted by the HadCM3 GCM experiments MidPlio\textsuperscript{Control} (thin black curve), EarlyPlio\textsuperscript{Control} (thick grey curve) and pre-industrial (dashed curve) (Haywood et al. 2007; Lunt et al. 2008a). Note the generally warmer temperatures for the Pliocene experiments and the variability in temperatures compared with the pre-industrial experiment. Standard deviations are pre-industrial = 0.69, MidPlio\textsuperscript{Control} = 0.89, and EarlyPlio\textsuperscript{Control} = 0.57. These results illustrate the range of potential behaviours of Pliocene ENSO to changing geological boundary conditions (e.g. ocean gateway configurations).
and to test Mid-Pliocene climate scenarios generated by numerical climate models. The MART technique, developed by O’Dea & Okamura (2000), uses the variation in zooid size within a colony to interpret the MART experienced by the colony. To date, over 150 Pliocene colonies collected from fossil localities ranging from Panama to the UK have been analysed to provide MART estimates, providing a new way to quantify changes in surface and near-surface ocean temperature seasonality.

The aims of this volume are threefold. Firstly, it is to synthesize the current state of knowledge regarding warm climates and environments of the Pliocene (e.g. papers by Dowsett & Robinson 2009; Dowsett et al. 2009; Dwyer & Chandler 2009; Matthiessen et al. 2009; Williams et al. 2009). As such the publication builds upon the foundations laid by two previous special issues on the Pliocene published in the journals Quaternary Science Reviews in 1991 and Marine Micropalaeontology in 1996. Secondly, the focus of the papers presented is to address fundamental questions about the workings of the Pliocene Earth system, which have been raised in this introduction (e.g. Bonham et al. 2009; Dowsett & Robinson 2009; Dowsett et al. 2009; Naish & Wilson 2009). Finally, papers are included that make a direct assessment of how similar Pliocene environments and climates may have been to climate and environmental predictions for the late twenty-first century (e.g. Dowsett et al. 2009; Lunt et al. 2009; Salzmann et al. 2009), exploring the value of examining warm climate states in Earth’s history as a potential analogue for future climate change.

References


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