It has been suggested that, during the Pliocene (ca 5–1.8 Ma), an El Niño state existed as a permanent rather than an intermittent feature; that is, the tropical Pacific Ocean was characterized by a much weaker east–west gradient than today. One line of inquiry used to investigate this idea relates modern El Niño teleconnections to Pliocene proxy data by comparing regional differences in precipitation and surface temperature with climate patterns associated with present-day El Niño events, assuming that agreement between Pliocene data and observations of modern El Niño events supports this interpretation. Here, we examine this assumption by comparing outputs from a suite of Mid-Pliocene climate simulations carried out with the UK Met Office climate model. Regional patterns of climate change associated with changes in model boundary conditions are compared with observed El Niño–Southern Oscillation teleconnection patterns. Our results indicate that many of the proposed ‘permanent El Niño’ surface temperature and precipitation patterns are observable in Mid-Pliocene climate simulations even when they display variability in tropical Pacific sea surface temperatures (SSTs) or when forced with a modern east–west SST gradient. Our experiments highlight the possibility that the same outcome may be achieved through different initial conditions (equifinality); an important consideration for reconstructed patterns of regional Mid-Pliocene climate.

Keywords: Pliocene; El Niño; El Niño–Southern Oscillation; teleconnections; climate models; equifinality

1. Introduction

(a) The El Niño–Southern Oscillation and ENSO prediction

The El Niño–Southern Oscillation (ENSO) is a coupled ocean–atmosphere phenomenon centred in and over the tropical Pacific Ocean. It involves large-scale decadal to interannual fluctuations in a number of oceanic and atmospheric
variables such as sea surface temperature (SST) and sea-level pressure. El Niño (warm phase) and La Niña (cold phase) episodes are the opposite extremes of the ENSO phenomenon. During an El Niño event, lower air pressure in the east weakens the westward atmospheric pressure gradient leading to unusually high SSTs extending across the central and eastern tropical Pacific Ocean and enhanced convection over this area. During a La Niña event, SSTs in the central and eastern equatorial Pacific (EEP) return to ‘normal’ and the trade winds strengthen, amplifying the oceanic temperature gradient so that anomalously low SSTs are recorded throughout much of the central and eastern tropical Pacific Ocean. ENSO is intimately linked with interannual climate variability and extreme climatic events around the world (e.g. droughts in east Australia, floods in Africa and Europe and the failure of the Asian monsoon; Charles et al. 1997).

ENSO represents a considerable challenge for general circulation models (GCMs), due to the many interacting ocean and atmospheric processes and its sensitivity to variations in climate boundary conditions. It is only relatively recently that GCMs have produced ENSO-like behaviour as an emergent property of the models. GCMs now simulate ENSO with varying degrees of fidelity (Guilyardi 2006), making some suitable tools for investigating sensitivities of ENSO to both past and future changes in climate boundary conditions; the latter being of considerable economic and socio-political relevance in the case of enhanced levels of greenhouse gases. For example, Collins (2000a), using version 2 of the Hadley Centre coupled model (HadCM2), found that quadrupling the pre-industrial levels of CO₂ caused ENSO events to become larger in amplitude and more frequent than present-day ENSO events. Thus, an additional effect of climate change would be greater impacts of ENSO events. However, using version 3 of the Hadley Centre coupled model (HadCM3), Collins (2000b) found that the magnitude and frequency of ENSO events remained unchanged as greenhouse gases increased. The range of uncertainty in the future behaviour of ENSO increases when one examines the responses of other atmosphere–ocean GCMs (Cubash et al. 2001; Collins and CMIP Modelling Groups 2005). Therefore, we are unable to say with certainty what will happen to the mean state or amplitude and frequency of ENSO in the future (Achutarao & Sperber 2002; Solomon et al. 2007). Studying past variations in climate and ENSO by comparing model predictions with palaeoclimate data presents an opportunity to evaluate GCMs with the goal of quantifying and ultimately reducing this uncertainty.

(b) Geological signatures of ENSO and model evaluation

Information regarding the behaviour of ENSO during radically different climate states of the past can be found within the geological proxy climate record. This geological resource can provide important clues to the variability of this ocean–atmosphere phenomenon through data with which to test palaeoclimate models (e.g. Brown et al. 2006). For example, Koutavas et al. (2006) analysed the oxygen isotope composition of individual foraminifera (Globigerinoides ruber) from four marine cores in the east and west tropical Pacific and successfully identified an attenuation of ENSO amplitudes for the Mid-Holocene. Tudhope et al. (2001), using annually banded corals from Papua New Guinea, showed that ENSO has existed for at least the past 130 000 years and operated...
even during glacial times of substantially reduced regional and global temperatures and changed solar forcing. They also found that during the twentieth century, ENSO has been strong compared with ENSO of previous cool (glacial) and warm (interglacial) times, and concluded that the observed pattern of change in amplitude may be due to the combined effects of ENSO dampening during cool glacial conditions and ENSO forcing by precessional orbital variations. Such studies have proven invaluable for testing the sensitivity of ENSO to climate change but are unable to examine the response of ENSO to a substantially warmer mean climate caused by increased atmospheric concentrations of greenhouse gases. Therefore, these studies do not represent a true palaeo-analogue for examining the potential behaviour of ENSO in the future.

Huber & Caballero (2003), combining palaeoclimate modelling with spectral analysis of varve thickness from two Middle Eocene lake sediment records in Wyoming (USA) and Eckfield Maar (Germany), showed a Pacific deep-ocean and high-latitude surface warming of approximately 10°C. However, the tropical thermocline structure, atmosphere–ocean dynamics and ENSO were similar to the modern. Although extremely useful as a test of ENSO dynamics to significantly increased levels of CO₂ in the atmosphere, the results from this Middle Eocene case study cannot be directly related to future ENSO behaviour due to complicating factors of significantly altered continental positions, global vegetation types and solar luminosity. The best geological analogue would require a warmer than present global mean climate, at least in part due to elevated atmospheric greenhouse gas concentrations, while maintaining similar to modern continental positions, ocean circulation patterns and vegetation types.

(c) ENSO during the Mid-Pliocene

The most recent interval of greater than present global warmth is the Mid-Pliocene warm period (ca 3.3–3.0 Myr ago), characterized by global surface temperatures approximately 3°C higher than today (e.g. Haywood & Valdes 2004). Mid-Pliocene climate can be used to understand processes contributing to long-term global warmth and ENSO behaviour, as many geological boundary conditions were similar to today (e.g. ocean gateways, continental positions), and atmospheric carbon dioxide concentrations were elevated approximately 30 per cent higher than pre-industrial values (e.g. Raymo et al. 1996).

Several papers have suggested that an El Niño condition was a permanent feature of Pliocene climate rather than oscillating between La Niña and El Niño states (e.g. Molnar & Cane 2002; Philander & Fedorov 2003; Barreiro et al. 2005; Wara et al. 2005; Fedorov et al. 2006). ‘Permanent El Niño’ is a rather loose and potentially confusing term, and here we interpret it as a state in which the west-to-east temperature gradient in the tropical Pacific is considerably weaker than today (with the potential for uniform SSTs across the basin) and ENSO variability is almost completely absent. We would expect the atmospheric circulation to respond to such differences, but we make no assumptions about the mean state of the ocean below the surface. If an El Niño state was a permanent feature of the Mid-Pliocene, it could be expected that temperatures in the EEP were higher, the thermocline in the region deeper and the Hadley circulation strengthened relative to today (Molnar & Cane 2002). It has also been proposed that the termination of a permanent El Niño-like state may have been a positive
forcing mechanism for the intensification of Northern Hemisphere glaciation ca 2.7 Ma BP (Cane & Molnar 2001; Philander & Fedorov 2003; Huybers & Molnar 2007). This state has recently been referred to as El Padre (A. C. Ravelo 2007, personal communication) in recognition of the fact that a mean state warming in EEP SSTs does not necessarily imply the presence of a permanent El Niño.

A number of palaeoceanographic studies have examined the development of the thermocline and SST gradient in the tropical Pacific over the last 5 Myr. Both Cannariato & Ravelo (1997) and Chaisson & Ravelo (2000) recorded a cooling of surface water in the EEP using δ¹⁸O measured in the surface-dwelling Globigerinoides sacculifer and deeper-dwelling Globorotalia tumida. Cannariato & Ravelo (1997) observed that δ¹⁸O in the east was lighter between ca 5 and 4 Ma, suggesting that surface waters of the eastern Pacific may have been warmer than they are today. Chaisson & Ravelo (2000) found that differences in δ¹⁸O between the two species decreased after 4.2 Ma, from which they surmised that the deep dwellers lived in increasingly cooler water, indicating that the thermocline in the EEP has shoaled since 4.2 Ma.

However, since the δ¹⁸O of carbonate is controlled by temperature and salinity, seasonal variations in salinity have the potential to confuse δ¹⁸O temperature records (Rickaby & Halloran 2005). Additional reconstructions of SST in the equatorial Pacific have been conducted based on other SST proxies, such as Mg/Ca ratios (e.g. Wara et al. 2005), the alkenone unsaturation index (U₃₇; Ravelo et al. 2006) and foraminiferal species assemblages (e.g. Dowsett 2007; Dowsett & Robinson 2009). Two studies of equatorial SSTs published in 2005 by Rickaby and Halloran and Wara et al. used analyses of Mg/Ca ratios measured in planktonic foraminifera shells to generate SST records from the western equatorial Pacific (WEP) and EEP from 5.3 Ma to present. From the results obtained, Rickaby & Halloran (2005) suggested that the SST of the WEP warm pool remained relatively stable and consistently warmer than the EEP, and that the Pliocene was characterized by permanent La Niña conditions. Despite using the same methodology and site selection, the results from Wara et al. (2005) contradict Rickaby & Halloran (2005) and conclude that, until ca 1.7 Ma, the west-to-east gradient was relatively small, with the SST difference always being less than 2°C (Wara et al. 2005). Together with previous studies of δ¹⁸O records (Cannariato & Ravelo 1997; Chaisson & Ravelo 2000), Wara et al. (2005) concluded that their results show the Pliocene was characterized by permanent El Niño-like conditions. The conclusion of Wara et al. (2005) was later corroborated by Haywood et al. (2005) and Ravelo et al. (2006) who, using an alkenone unsaturation index (U₃₇)-based SST record from the EEP, indicated that, in the Early Pliocene, the east–west asymmetry in SST and thermocline depth was reduced compared with the present day. The faunal assemblage approach also confirms a reduced east–west gradient in the Mid-Pliocene, supporting the idea that the tropical Pacific was in a permanent El Niño-like state (Dowsett & Robinson 2009).

Despite these previous studies, it remains uncertain whether a permanent El Niño condition existed during the Early and Late Pliocene. Rickaby & Halloran (2005) and Wara et al. (2005) have provided conflicting interpretations of the same datasets to the mean state changes to equatorial Pacific SSTs. Since ENSO events occur over decadal to subdecadal time scales, the temporal resolution of the data (at best representing one sample per few thousand years) is such that...
current palaeoceanographic records are not capable of proving the existence of either a permanent El Niño or La Niña state during the Pliocene (Haywood et al. 2007). Furthermore, a recent fully coupled ocean–atmosphere modelling study for the Mid-Pliocene has demonstrated that continuing variability between La Niña and El Niño conditions is not necessarily inconsistent with a mean SST warming in the EEP (Haywood et al. 2007).

As an independent line of investigation, Molnar & Cane (2002) tested the theory of a permanent El Niño by comparing teleconnections associated with modern El Niño with Pliocene proxy data collected in the extratropics. Typical modern El Niño teleconnections include warmer temperatures over Canada and Alaska (mainly in winter) and a cooler, slightly wetter climate around the Gulf of Mexico (see Graham (1989a,b), Ager (1994) and Wolfe (1994) for the corresponding Pliocene proxy data). A drier northeastern South America has also been noted as a prominent teleconnection with El Niño (Ropelewski & Halpert 1987, 1996; Trenberth et al. 1998).

Table 1 summarizes the temperature and precipitation data (reconstructed using mainly fossil assemblages; Zarate & Fasana 1989; Cronin & Dowsett 1990; Wolfe 1994) for the Pliocene extratropics that have been used by Molnar & Cane (2002) to support a permanent El Niño climate pattern. Overall, there is a mixed correlation between the data from the Pliocene and the corresponding areas where teleconnections are expected. Some areas, such as northeast South America and northwest Canada, show climates similar to those experienced during an El Niño event, while other areas such as parts of Africa, Asia and Australia generally do not resemble any anomalies associated with typical El Niño teleconnections, with the exception of the 1997–1998 El Niño event (Molnar & Cane 2007).

In this paper, we re-examine the concept of using patterns of regional Pliocene climate change reconstructed using a diverse range of geological proxy data sources to support the premise of a Pliocene permanent El Niño state. In doing so, we also explore the possibility of equifinality, where different initial conditions may produce the same outcome, in this instance the regional patterns of temperature and precipitation are observed. In essence, we aim to determine whether regional climate change during the Mid-Pliocene can be attributed solely to a permanent El Niño condition or whether equifinality in the Pliocene Earth system makes alternative explanations possible.

Initially, we compare the results from two Mid-Pliocene model simulations using fixed and predicted SSTs that either do not display a significant warming of annual mean SSTs in the EEP (hence maintaining a strong SST gradient across the tropical Pacific) or display a warming of mean annual SST in the EEP (hence El Niño-like) but exhibit clear climate variability over ENSO time scales (i.e. permanent ENSO rather than El Niño). We then diagnose the relative contribution of boundary condition changes to regional Mid-Pliocene climate variability by presenting results from a suite of fully coupled ocean–atmosphere GCM simulations, which track the major environmental boundary condition changes that have occurred from the pre-industrial to the Mid-Pliocene. These changes are made incrementally to facilitate identification of the relative importance of each change and to identify whether or not these changes alone are sufficient to generate regional climate patterns which are similar to those that occur during modern El Niño events.

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Table 1. Summary of the global Pliocene data for temperature and precipitation cited in Molnar & Cane (2002).

<table>
<thead>
<tr>
<th>area and season</th>
<th>proxy</th>
<th>temperature/precipitation</th>
<th>reference</th>
</tr>
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<tbody>
<tr>
<td>Japan</td>
<td>DJF molluscs, diatoms and ostracodes that lived between 3.4 and 2.3 Ma pollen taxa found in warmer parts of China today Mid-Pliocene radiolaria</td>
<td>relatively warmer water adjacent to Japan; cooling trend after 2.7 Ma ODP sites offshore (south) indicate warmer temperatures warmer inland, cooler offshore indicate warm humid climate</td>
<td>Cronin et al. (1994) Momohara (1994)</td>
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<tr>
<td>North America and Canada</td>
<td>DJF pollen and spore assemblages</td>
<td>north of the Alaska Range, in eastern Alaska and in the Yukon; warmer temperatures</td>
<td>Ager (1994)</td>
</tr>
<tr>
<td></td>
<td>fossil leaf assemblages (5.9 Ma)</td>
<td>mean annual temperatures in the Alaskan Range above 3°C</td>
<td>Wolfe (1994)</td>
</tr>
<tr>
<td></td>
<td>pollen assemblages</td>
<td>northeast Canada and eastern North Carolina; 4–10°C warmer</td>
<td>Willard (1994)</td>
</tr>
<tr>
<td></td>
<td>Mid-Pliocene fossils of a tortoise, turtles and alligators</td>
<td>Beck Ranch in the middle of Texas; wetter</td>
<td>Thompson (1991)</td>
</tr>
<tr>
<td></td>
<td>used present-day habitats of ostracods to assign palaeoenvironments to fossil taxa</td>
<td>south Florida and South Carolina; 1–2°C cooler</td>
<td>Cronin &amp; Dowsett (1990, 1996); Cronin (1991)</td>
</tr>
<tr>
<td></td>
<td>Mid-Pliocene foraminifera</td>
<td>northeast coast of North America; warmer</td>
<td>Dowsett &amp; Poore (1990, 1991)</td>
</tr>
<tr>
<td></td>
<td>Early to Mid-Pliocene pollen and ostracods</td>
<td>Florida and east coast of North America; cooler Early Pliocene and warmer Mid-Pliocene</td>
<td>Willard et al. (1993)</td>
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Table 1. (Continued.)

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<thead>
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<th>area and season</th>
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<th>temperature/precipitation</th>
<th>reference</th>
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<tr>
<td></td>
<td>JJA</td>
<td>absence of continental ice sheets during Early Pliocene</td>
<td>Haug <em>et al.</em> (1999)</td>
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<td></td>
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<td>modern habitats of fossil lacustrine ostracodes and fishes in palaeolakes (4.5–2.8 Ma)</td>
<td></td>
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<td></td>
<td></td>
<td>Mid-Pliocene spring and lake deposits</td>
<td>Smith &amp; Patterson (1994)</td>
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<td></td>
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<td>Mid-Pliocene pollen</td>
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<tr>
<td>South America</td>
<td>DJF</td>
<td>Late Pliocene vertebrate fossils</td>
<td>Zarate &amp; Fasana (1989)</td>
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<td></td>
<td></td>
<td>Mid-Pliocene fossil assemblages</td>
<td>Graham (1989a,b)</td>
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<td></td>
<td></td>
<td>Mid-Pliocene aeolian deposits</td>
<td>Hovan (1995)</td>
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Note: The table continues from the previous page with more entries.
2. Methods

(a) Model description

The Hadley Centre coupled model (hereafter referred to as HadCM3) is one of the world’s leading GCMs, which has been used in each of the IPCC assessment reports. The particulars of the model are well documented and its general performance has been assessed in previous work (e.g. Gordon et al. 2000; Pope et al. 2000). However, some discussion of the model itself is necessary. HadCM3 was developed at the Hadley Centre, which is a part of the UK Met Office. The model requires no flux corrections to be made even for simulations of a thousand years or more (Gregory & Mitchell 1997). The GCM consists of a coupled atmospheric model, ocean model, vegetation model and sea-ice model. The horizontal resolution of the atmospheric model is 2.5° in latitude by 3.75° in longitude. This gives a grid spacing at the equator of 280 km in the north–south direction and 420 km east–west. The atmospheric model consists of 19 vertical layers. The atmospheric model has a time step of 30 minutes and includes a radiation scheme that can represent the effects of major and minor trace gases (Edwards & Slingo 1996). A parametrization of simple background aerosol climatology is also included (Cusack et al. 1998). The convection scheme is that of Gregory et al. (1997). A land-surface scheme includes the representation of the freezing and melting of soil moisture. The representation of evaporation includes the dependence of stomatal resistance on temperature, vapour pressure and CO₂ concentration (Cox et al. 1999).

The spatial resolution over the ocean in HadCM3 is 1.25° × 1.25°, and the model has 20 vertical layers. The ocean model includes the use of the Gent–McWilliams mixing scheme (Gent & McWilliams 1990). There is no explicit horizontal tracer diffusion in the model. The improved horizontal resolution allows the use of a smaller coefficient of horizontal momentum viscosity leading to an improved simulation of ocean velocities. The sea-ice model uses a simple thermodynamic scheme and contains parametrizations of ice drift and leads (Cattle & Crossley 1995).

(b) Experimental design

Seven model experiments are presented in this paper, two for the pre-industrial, two for the Mid-Pliocene, and three sensitivity experiments tracking the major boundary condition changes that occurred from the pre-industrial to the Mid-Pliocene. Our control Mid-Pliocene experiments (hereafter referred to as PlioFixedSST and PlioControl, respectively) were initialized with Mid-Pliocene boundary conditions derived from the US Geological Survey (USGS) PRISM2 dataset (see §2c for further details). PlioFixedSST is an atmosphere-only GCM experiment with fixed SSTs (as presented in Haywood & Valdes 2006), while PlioControl is a fully coupled ocean–atmosphere GCM experiment that represents a ca 700 year continuation of the experiment presented in Haywood & Valdes (2004). PlioFixedSST and PlioControl were compared against their equivalent pre-industrial runs, ControlFixedSST and PreIndCoupled, respectively. The purpose of these experiments is twofold. First, the PRISM2 dataset exhibits no warming of EEP SSTs; hence, the SST gradient from west to east is unchanged relative to modern in experiment PlioFixedSST. This facilitates the identification of regional
Mid-Pliocene climate changes that are not the result of a warming in the EEP. Second, experiment Plio\textsuperscript{Control} does exhibit a mean state warming of EEP SSTs by 2–3°C, which could be used to support the premise of a permanent El Niño state for the Early and Late Pliocene. However, the model predicts clear alterations between El Niño and La Niña states (Haywood et al. 2007), facilitating an examination of regional climate changes that may be linked to a mean state SST change in the EEP, but not associated with a permanent El Niño condition.

In order to identify the important mechanisms that have determined changes in ENSO behaviour since the Mid-Pliocene, we present results from the three sensitivity experiments (hereafter referred to as PreInd\textsuperscript{Plioveg}, PreInd\textsuperscript{Pliovegorog} and PreInd\textsuperscript{Pliovegorogice}) to be compared with a fully coupled ocean–atmosphere pre-industrial control experiment (referred to as PreInd\textsuperscript{Coupled}). In this ensemble, we gradually move from the climate of the pre-industrial to that of the Mid-Pliocene, in a series of incremental steps.

The differences between these simulations are the atmospheric CO\textsubscript{2} concentration and the surface boundary conditions. There are, in fact, 22 surface boundary conditions that differ between the two simulations; examples include snow-free vegetation albedo, orography and heat capacity of the soil. It is clearly not possible to vary each one of these independently (more than four million simulations) or even sequentially (23 simulations). Instead, we group them together into classes, together representing similar processes and move sequentially between them. We choose three such classes: (i) vegetation and soils, (ii) orography, and (iii) ice, together with the atmospheric CO\textsubscript{2}. Further details of the resulting simulations are given in tables 2 and 3.

The differences between the pre-industrial and Mid-Pliocene vegetation, soils and ice extent is shown in figure 1\textsuperscript{a}, in terms of the snow-free albedo in the two cases. The largest differences are in the high latitudes, where there is bare soil/tundra (relatively high albedo) in the modern and boreal forest (lower albedo) in the Mid-Pliocene. This is particularly noticeable on the margins of Greenland, the Canadian archipelago and in southern Alaska.

The difference between the pre-industrial and Mid-Pliocene orography is shown in figure 1\textsuperscript{b}, in terms of the surface height. The most significant changes in terms of surface height in the Northern Hemisphere are the Rocky Mountains, which are higher by 1000 m in the pre-industrial compared with the Mid-Pliocene, and over Greenland itself where the increase in height is due to the larger modern ice sheet. In the Southern Hemisphere, the reduced Pliocene Antarctic ice sheet is evident. All of the Mid-Pliocene boundary conditions are derived from reconstructions derived from the PRISM project (see §2c; Dowsett et al. 1999).

A CO\textsubscript{2} concentration of 400 ppmv is used in experiments Plio\textsuperscript{FixedSST} and Plio\textsuperscript{Control}. This is a justifiable value when available proxy estimates of Mid-Pliocene atmospheric CO\textsubscript{2} concentrations are considered. Estimates have been derived from the analysis of stomatal density of fossil leaves (Van Der Burgh et al. 1993; Kürschner et al. 1996) and through analysis of δ\textsuperscript{13}C ratios of marine organic carbon (Raymo & Rau 1992; Raymo et al. 1996). All three proxy methods suggest that absolute CO\textsubscript{2} levels during the time period range from 360 to 400 ppmv, compared with the mid-nineteenth-century levels of approximately 280 ppmv and modern (2005) concentrations of 378 ppmv. For further details of the experimental design, see table 2.

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The Plio FixedSST and Plio Control simulations were integrated for 30 and 700 years, respectively (the former short integration time is justified as the atmosphere adjusts very quickly to changes in SST and other boundary conditions). Experiments PreInd Plioveg, PreInd Pliovegorog and PreInd Pliovegorogice represent 200-year continuation runs of our pre-industrial control experiment (PreIndCoupled) with the fully coupled ocean–atmosphere GCM. Climatological means were derived from the final 60 simulated years for all coupled ocean–atmosphere simulations and the final 20 years for atmosphere-only experiments running with prescribed SSTs. An analysis of the model’s energy imbalance at the top of the atmosphere (TOA) for all experiments is presented in Table 2. For all experiments, there is no observable trend in surface temperatures. Therefore, we consider that all of the model runs have reached an equilibrium state, at least in the upper ocean.

**Mid-Pliocene boundary conditions**

Required boundary conditions were supplied by the USGS PRISM2 $2^\circ \times 2^\circ$ digital dataset. The particulars of the PRISM2 dataset have been well documented in previous papers (Dowsett et al. 1999; Haywood et al. 2000 and...
references therein). In brief, the prescribed boundary conditions cover the time slab between 3.29 and 2.97 Ma according to the geomagnetic polarity time scale (Berggren et al. 1995). Boundary conditions integrated into the model that are specific to the Pliocene include: (i) continental configuration, modified by a 25 m increase in global sea level, (ii) modified present-day elevations, (iii) reduced ice-sheet size and height for Greenland (approx. 50% reduction) and Antarctica (approx. 33% reduction), (iv) Pliocene vegetation distribution, and (v) Pliocene SSTs and sea-ice distributions.

The geographical extent of the Greenland and Antarctic ice sheets within the PRISM2 dataset was based on global sea-level estimates derived for the Pliocene by Dowsett & Cronin (1990). The PRISM2 reconstruction uses model results from Michael Prentice (personal communication; cited in Dowsett et al. 1999) to guide the areal and topographic distribution of Antarctic and Greenland ice. A 25 m sea-level rise is equivalent to a maximum decrease in global average salinity of approximately 0.25 PSU, which is small and therefore was not included in our Pliocene coupled ocean–atmosphere simulations. For a more detailed description of the PRISM2 dataset and how it differs from earlier PRISM datasets, see Dowsett et al. (1999).

(d) HadCM3: simulation of modern ENSO

The ability of the HadCM3 GCM to simulate ENSO variability has obvious implications for this work. It has been established that HadCM3 has a good simulation of present-day ENSO (Collins et al. 2001; Achutarao & Sperber 2002).

Figure 1. (a) Vegetation and soil boundary conditions. Global snow-free surface albedo in (i) the pre-industrial and (ii) the Mid-Pliocene. Ice-sheet extent is visible in the high latitudes where the albedo is up to 0.8. (b) Global orography in (i) the pre-industrial and (ii) the Mid-Pliocene.
In a coupled model intercomparison project (CMIP) ensemble of flux-adjusted and non-flux-adjusted models, HadCM3 performed consistently well against observational data, capturing the variability in tropical Pacific surface air temperatures (SATs) as well as simulating correctly the timing of the annual cycle of Pacific SSTs and the amplitude of recent ENSO events (Achutarao & Sperber 2002).

To demonstrate the performance of HadCM3 in simulating modern ENSO teleconnections, we present regression coefficients between anomalies in observed and model-predicted SAT (figure 2) and precipitation (figure 3) and the NINO3.4 region, which is a common index of ENSO and relevant for both observations and

Figure 2. ENSO teleconnections from observations and HadCM3. (a) Regression coefficients, $\beta(x, y)$ ($^\circ$C/$^\circ$C), of (i) observed (HadCRUT3) mean annual SAT on annual NINO3.4 anomalies and (ii) modelled annual SAT on modelled HadCM3 NINO3.4 anomalies. (b) Regression coefficients, $\beta(x, y)$, of (i) observed December–February (DJF) SAT on DJF NINO3.4 anomalies and (ii) modelled DJF SAT on modelled HadCM3 NINO3.4 anomalies. (c) The same as in (b) but for June–August (JJA).

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To demonstrate the performance of HadCM3 in simulating modern ENSO teleconnections, we present regression coefficients between anomalies in observed and model-predicted SAT (figure 2) and precipitation (figure 3) and the NINO3.4 region, which is a common index of ENSO and relevant for both observations and

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HadCM3. Observed SATs and precipitation were derived from the HadCRUT3 dataset (Brohan et al. 2006) and CPC Merged Analysis of Precipitation (CMAP; Xie & Arkin 1997), respectively.

The regression model used is

$$\theta(x, y, t) = \beta(x, y) \times \text{NINO3.4}(t) + \varphi(x, y, t),$$

where anomalies in the three-dimensional climate variable, $\theta(x, y, t)$, which is a function of longitude, latitude and time (as indicated by $(x, y, t)$), are represented as a spatial map of regression coefficients, $\beta(x, y)$, multiplied by time-only varying NINO3.4 index. $\beta$ is calculated at each grid point using ordinary least-squares

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Figure 3. ENSO teleconnections from observations and HadCM3. (a) Regression coefficients, $\beta(x, y)$ (mm d$^{-1}$ K$^{-1}$), of (i) observed mean annual precipitation and (ii) modelled annual precipitation on modelled HadCM3 NINO3.4 anomalies. (b) Regression coefficients, $\beta(x, y)$, of (i) observed December–February (DJF) precipitation on DJF NINO3.4 anomalies and (ii) modelled DJF precipitation on modelled HadCM3 NINO3.4 anomalies. (c) The same as in (b) for June–August (JJA).

HadCM3. Observed SATs and precipitation were derived from the HadCRUT3 dataset (Brohan et al. 2006) and CPC Merged Analysis of Precipitation (CMAP; Xie & Arkin 1997), respectively.
regression and results in a residual or ‘noise’ term \( \varphi(x, y) \), which captures the non-ENSO-related variability. The approach is widely used to characterize teleconnection patterns.

HadCM3 reproduces ENSO annual mean SAT teleconnections reasonably well, showing the observed warming over northwest Canada and Alaska and cooling over southern North America during warm events, although this area has a greater northward extent in the model (figure 2a). Europe and Asia also show a good correlation with the observed changes. The largest discrepancies from the observed SAT trends occur over South America and northeast Canada, where, rather than reproducing the slight warming seen in the observational data, the model indicates cooler temperatures than the mean.

This difference is slightly reduced looking at the seasonal data (December–February, DJF; June–August, JJA), which indicates that the model provides a better correspondence with the observed data over South America and Australia during DJF and northeast Canada during JJA (figure 2b,c).

The observed precipitation patterns are also reproduced fairly well in the model, although the area of decreased precipitation over the WEP appears to extend further north in the observed data (figure 3a). This difference is likely to be due to biases in the time-mean SSTs in the WEP. The area of increased rainfall over the equator extends slightly further east in the model compared with the data; however, in general, particularly in the seasonal data, the patterns seen across the Pacific match reasonably well (figure 3b,c).

In summary, with the exception of a few local areas, HadCM3 reproduces the observed temperature and precipitation anomalies associated with ENSO relatively well. Many of the teleconnections associated with an El Niño event, such as a warming over Canada and reduced rainfall in the WEP, are present in the model.

3. Results

(a) Comparison of the observed ENSO and Mid-Pliocene climate patterns

Figure 4 shows the difference in seasonal (DJF and JJA) SAT (°C) and precipitation (mm d\(^{-1}\)) between experiments Plio\(^{\text{FixedSST}}\) and Control\(^{\text{FixedSST}}\) and the same differences between the Plio\(^{\text{Control}}\) and PreInd\(^{\text{Coupled}}\) simulations. The geographical patterns of these differences in DJF and JJA SATs/precipitation are compared with the observed ENSO SAT and precipitation patterns presented in figures 2 and 3.

The most significant differences between the Mid-Pliocene and pre-industrial scenarios occur in the mid- to high latitudes of the Northern Hemisphere during DJF. Relative to Control\(^{\text{FixedSST}}\), experiment Plio\(^{\text{FixedSST}}\) (figure 4a) exhibits higher SATs over northwest Canada and Alaska (approx. 3–5°C in both seasons), which are comparable with the teleconnections observed by the regression coefficient for SATs presented in figure 2b. South America also shows similar temperature patterns to the observed ENSO teleconnections, with higher DJF SATs in the north (approx. 2–3°C) and lower SATs in the south (approx. 3–5°C).

There are some areas where SAT differences between experiments Plio\(^{\text{FixedSST}}\) and Control\(^{\text{FixedSST}}\) do not match observed ENSO patterns. These include southern North America as well as parts of Asia and the Middle East and Australia (DJF),
which have warmer temperatures relative to the pre-industrial run and observational data for ENSO teleconnections. A warming also occurs in South Africa during DJF, which is not present in the Plio$^{\text{Fixed SST}}$ simulation (figure 4a).
Observed precipitation changes associated with ENSO (figure 3) occur along the equator, particularly across the equatorial Pacific, where a significant increase in precipitation in the central Pacific and EEP (2–5 mm d\(^{-1}\)) and a decrease in precipitation in the WEP (1–2.5 mm d\(^{-1}\)), which extends beyond Australia during DJF, can be seen. There is also a reduction in precipitation (0.5–1 mm d\(^{-1}\)) over southeast Africa and northwest South America, which continues across the South Atlantic. Precipitation increases occur over the North Atlantic, Asia/Europe and Greenland during DJF (0–0.5 mm d\(^{-1}\)).

Several of the observed patterns described above can be seen in figure 4c, with precipitation in experiment Plio\(^{\text{FixedSST}}\) increasing over Greenland (DJF), the North Atlantic, and southeast South America and across Siberia (DJF) by approximately 0.2–4 mm d\(^{-1}\) relative to experiment Control\(^{\text{FixedSST}}\). Precipitation patterns over northeast South America and across the South Atlantic in DJF in experiment Plio\(^{\text{FixedSST}}\) are also similar to the observed teleconnections patterns, being approximately 0.2–4 mm d\(^{-1}\) drier than today. The reduced precipitation over the WEP and off the east coast of Australia is also present in experiment Plio\(^{\text{FixedSST}}\), receiving 1–8 mm d\(^{-1}\) less precipitation. However, over the central and EEP, experiment Plio\(^{\text{FixedSST}}\) appears to be drier, and the precipitation patterns do not match the observed ENSO patterns.

Figure 4b shows the difference between the Plio\(^{\text{Control}}\) (with ENSO variability) and the PreInd\(^{\text{Coupled}}\) simulations for SAT. Comparison of these patterns with observed ENSO teleconnections show several similarities; temperatures over northwest Canada and Alaska, for example, are higher in Plio\(^{\text{Control}}\) compared with the pre-industrial run, as well as over northern South America and Central America, which experience higher temperatures of approximately 2–6°C. There is also an area off the coast of Japan that is approximately 8–10°C warmer in the Plio\(^{\text{Control}}\) experiment. However, the temperature and precipitation values predicted for the Gulf of Mexico during DJF in experiment Plio\(^{\text{Control}}\) are slightly warmer and drier than the pre-industrial run, whereas the observed ENSO teleconnections show this area to be cooler and wetter.

The observed reductions in precipitation over northeast South America, southeast Africa and over the WEP associated with ENSO can be seen in figure 4d, with the Plio\(^{\text{Control}}\) run being 0.5–4 mm d\(^{-1}\) drier than the pre-industrial scenario. Precipitation over the EEP in DJF is greater in the Plio\(^{\text{Control}}\) run, although this decreases during JJA.

(b) Sensitivity experiments: from the pre-industrial to Mid-Pliocene

Many of the teleconnection patterns associated with a modern El Niño are believed to have been present in the Pliocene based on multi-proxy data taken at various locations around the globe (Molnar & Cane 2002). These data have been used to support previous studies based on the EEP (e.g. Chaisson & Ravelo 2000; Wara et al. 2005; Ravelo et al. 2006), which have suggested permanent El Niño-like conditions. The results in §3a, however, indicate that many of these teleconnections occur without a permanent El Niño, but with ENSO variability or an unchanged SST gradient across the equatorial Pacific.

In this section, we analyse outputs from sensitivity experiments PreInd\(^{\text{Plioveg}}\), PreInd\(^{\text{Pliovegorog}}\) and PreInd\(^{\text{Pliovegorogice}}\) and the Plio\(^{\text{Control}}\) control, with increased CO\(_2\) levels (table 2), to look at alternative factors that could create the temperature and precipitation patterns outlined in §3a.

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The effect of Mid-Pliocene vegetation

With just the vegetation altered to represent Mid-Pliocene conditions, global temperatures in the Southern Hemisphere remain similar to pre-industrial values, with the majority of South America, southern Africa and Australia showing few of the SAT patterns outlined in §3a (figure 5a). Australia also has a large area where temperatures during JJA are higher than the PreInd\textsuperscript{Coupled} rather than showing the lower regional temperatures seen in the observed data.

It is important to note that the HadCM3 GCM uses Thompson & Fleming’s (1996) Mid-Pliocene vegetation reconstruction, in which data in the Southern Hemisphere are relatively sparse. In such cases, areas where there are gaps in the Mid-Pliocene data have been filled in with modern estimates (e.g. over South America). It is therefore unsurprising that larger differences in climate are

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(i) The effect of Mid-Pliocene vegetation

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It is important to note that the HadCM3 GCM uses Thompson & Fleming’s (1996) Mid-Pliocene vegetation reconstruction, in which data in the Southern Hemisphere are relatively sparse. In such cases, areas where there are gaps in the Mid-Pliocene data have been filled in with modern estimates (e.g. over South America). It is therefore unsurprising that larger differences in climate are
associated with vegetation change in the Northern Hemisphere, where the abundance of Mid-Pliocene data allows a more complete view of the difference between the Pliocene and pre-industrial vegetation. Here, the SAT differences between PreIndPlioveg and PreIndCoupled are more apparent, with PreIndPlioveg having higher temperatures over the majority of the area (figure 5a). One exception to this pattern occurs over India, which has lower temperatures than PreIndCoupled, whereas in the observed data, this region experiences warmer temperatures during a modern El Niño event (figure 2).

The main area where the temperature differences are similar to the observed SAT teleconnection patterns is northwest Canada and Alaska where temperatures are approximately 1–3°C higher than the pre-industrial run during DJF (figure 5a). Over the rest of North America, the temperature difference between PreIndPlioveg and PreIndCoupled decreases between DJF and JJA, although the temperatures are still higher than PreIndCoupled, whereas, in the observed data, the SATs cool over summer.

Altering the vegetation does not have a large effect on the precipitation, and there is generally little difference between the global precipitation patterns for the PreIndPlioveg and PreIndCoupled runs over DJF with the exception of a few areas. These include regions of reduced precipitation over the Indian Ocean and Pacific Ocean, south of Japan by approximately 0.5–4 mm d\(^{-1}\) and increased precipitation over northwest South America of approximately 0.1–2.0 mm d\(^{-1}\) (figure 6a). A clear band of higher precipitation can also be seen across North America, starting off the southwest coast and extending northeast past Greenland. Over the equatorial Pacific, there is little difference between precipitation patterns for PreIndPlioveg and PreIndCoupled, whereas, in the observed teleconnection data, it is an area of high variability.

Over JJA, the differences in the precipitation patterns between PreIndPlioveg and PreIndCoupled increase, particularly along the equator and high latitudes that receive greater precipitation than PreIndCoupled (up to 4 mm d\(^{-1}\) more). While over South America, precipitation decreases in PreIndPlioveg to 0.2–1 mm d\(^{-1}\) less rainfall than in PreIndCoupled (figure 6a).

(ii) *The effect of Mid-Pliocene orography*

Altering the elevation of the orography, as well as the vegetation, increases SATs over India, Australia (DJF) and northern South America by 1–4°C compared with the pre-industrial coupled run (figure 5b). Temperatures over South Africa also increase by 1–3°C. These temperature patterns provide a better correlation with the regional patterns observed during a modern El Niño in these areas compared with the results of PreIndPlioveg. The SATs over southeast South America also decrease to become approximately 1–3°C lower than the pre-industrial temperatures. This band of lower SATs can be seen in the observed teleconnection data, although to a much larger extent (figures 6b and 2b). To the east of the Rockies (JJA) and across northeast America (DJF), temperatures increase to become higher than those seen in PreIndCoupled. Interestingly, altering the elevation of the Rocky Mountains decreases temperatures over Canada and Alaska, with this area now being 1–3°C cooler than the pre-industrial run and reaching up to approximately 9°C cooler offshore (figure 7a). This pattern also occurs off the northeast coast of Japan, where temperatures have decreased as a

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result of altering the orography, this time by approximately 8°C compared with the previous run PreInd Plioveg and approximately 3°C compared with the pre-industrial run (figure 5b).

Changing the orography to resemble that of the Mid-Pliocene has the greatest impact on the global precipitation patterns, significantly increasing the magnitude and extent of the patterns that were seen in PreInd Plioveg. The most prominent changes occur over the equatorial regions (figure 8a) and high northern latitudes (figure 6b). During DJF, northeast South America and the WEP receive up to 4 mm d$^{-1}$ less precipitation compared with PreInd Coupled and the previous run PreInd Plioveg. The tropics, North America (DJF), South America (northwest and southeast) and across western Europe, on the other hand, receive up to 4 mm more rainfall per day (figures 6b and 9a). This pattern alters slightly over JJA, with precipitation decreasing over North America, in a band that runs along the eastern side of the Rocky Mountains, and over the majority of South America by approximately 0.2–1.0 mm d$^{-1}$ less. The extent of
this pattern of reduced precipitation over South America in JJA is slightly larger than that seen in the observed data. Southern Africa receives less precipitation in the east compared with the PreIndCoupled, but a greater amount over the west by 1–2 mm d\(^{-1}\) (figures 6b and 8a), both patterns matching the regional precipitation patterns seen in §3 and in the observed teleconnection data.

Across the Pacific, large precipitation changes are noticeable as a result of altering the orography, with an area of reduced precipitation appearing off the east coast of Australia, as well as a band of increased precipitation across

Figure 7. SAT (°C) differences for North America, (i) for DJF and (ii) JJA, shown for anomalies exceeding a 95% statistical confidence level, between (a) PreIndPlioveg and PreIndPliovegorog showing the effects of orography, (b) PreIndPliovegorog and PreIndPliovegorogice showing the effects of reducing the extent of the ice sheets and (c) PreIndPliovegorogice and PlioControl showing the effect of increasing CO\(_2\) levels in the atmosphere.
the equatorial Pacific. This area extends westward so that the islands around Indonesia receive more precipitation compared with the PreInd Coupled run; however, compared with the observed teleconnection data, this is too far west (figures 6b and 8a). There is also a stronger signal of reduced precipitation over the northwest Pacific Ocean, which extends northeast across to Canada. This pattern is present in the observed data, although not to the same extent. The increase in precipitation over the region of the Kuroshio Current in the observed data is also seen in PreInd Pliovegorog, but the area is greatly reduced (figure 6b).

(iii) The effect of Mid-Pliocene ice sheets

Reducing the extent of the ice sheets has a significant effect on the global temperatures in the high latitudes, particularly during JJA, with both the Northern and Southern Hemispheres becoming much warmer than PreInd Coupled, reaching up to 15–20°C higher (figure 5c). The area of higher SATs across northern South America has also increased in extent. Temperatures off the coast of northwest Canada and Alaska remain cooler than the pre-industrial SATs; however, temperatures inland have once again increased and are 1–5°C higher (figures 5c and 7b).

Global precipitation patterns do not alter a great deal when the ice sheets are reduced, although there are a few areas in the high latitudes where the precipitation patterns differ from the previous run PreInd Pliovegorog. These

![Figure 8. Precipitation (mm d⁻¹) differences for the Southern Hemisphere between (a) PreIndPlioveg and PreIndPliovegorog (b) PreIndPliovegorog and PreIndPliovegorogice and (c) PreIndPliovegorogice and PlioControl for (i) DJF and (ii) JJA.](http://rsta.royalsocietypublishing.org/Downloaded from)
include over the North Atlantic during DJF, where precipitation levels over the storm track and Greenland appear to increase by approximately 1–2 mm d\(^{-1}\) (figures 6\(b\) and 9\(b\)).

(iv) **The effect of Mid-Pliocene CO\(_2\)**

Increasing CO\(_2\) levels also has a strong effect on SATs, resulting in higher global temperatures over most continental areas and the vast majority of the oceans relative to the PreInd\(^{\text{Coupled}}\) (figure 4\(b\)). This effect appears to be much more extensive than the warming that occurs after altering the orography in PreInd\(^{\text{Pliovegorog}}\) or ice sheets in PreInd\(^{\text{Pliovegorogice}}\) (figure 5\(c\)). Temperatures over northern South America, India, Australia (DJF only) and Canada are higher than PreInd\(^{\text{Coupled}}\) by approximately 2–8°C (figures 7\(c\) and 10\(c\)), while over southern South America (DJF only), temperatures reach up to 3°C lower (figure 4\(b\)).
Increasing CO₂ levels does not appear to have a large impact on the precipitation patterns compared with the PreInd Coupled (figure 4d). Comparing the CO₂ increase with the PreInd Pliovegorog and PreInd Pliovegorogice runs, however, shows some changes to the precipitation patterns. With greater levels of CO₂, precipitation over the North Atlantic storm track, Central America (JJA) and off the west coast of South America has reduced by up to 1 mm d⁻¹ and has increased over equatorial West Africa and the north Pacific by up to 0.5 mm d⁻¹ (figures 8c and 9c). Precipitation over the Gulf of Mexico also decreases with increased CO₂ levels. Generally though, the largest changes to the precipitation patterns occur when the orography is altered.

4. Discussion

A number of previous studies of the Pliocene have been focused on the EEP using multi-proxy data, such as δ¹⁸O isotopes, Mg/Ca ratios, alkenone unsaturation index (U₃₇) and foraminiferal species assemblages to reconstruct SST values in this area (e.g. Chaisson & Ravelo 2000; Haywood et al. 2005; Wara et al. 2005; Ravelo et al. 2006; Dowsett 2007). The results obtained in these studies show a pattern of SSTs across the equatorial Pacific similar to that seen during a modern El Niño event, where temperatures in the EEP are elevated and, in large events, can be as high as those in the WEP, leading to the suggestion of a permanent El Niño state present during the Pliocene. These results, although perhaps...
consistent with the presence of a permanent El Niño during the Pliocene, are not conclusive due to the low temporal resolution of the data that cannot capture the decadal and sub-decadal climate variations associated with ENSO.

An alternative study by Molnar & Cane (2002) compared teleconnection patterns produced as a result of a modern El Niño event with regional SAT and precipitation patterns obtained from global Pliocene proxy data. They collected several sources of geological data from various locations that show temperature and precipitation patterns similar to those observed during a modern El Niño. However, the proxy data used have a limited spatial extent, and many of the regional climate trends shown have been extrapolated from less than five data points.

This study aims to establish whether there are other possible explanations for the temperature and precipitation patterns observed. Two simulations for the Mid-Pliocene climate were initially conducted (table 2): one with no change in the SST gradient across the equatorial Pacific (Plio\(^{\text{FixedSST}}\)) and the other with a mean state warming in the EEP, but ENSO variability prescribed (Plio\(^{\text{Control}}\)). The outputs of these simulations were compared with the observed teleconnection patterns associated with a modern El Niño event to ascertain whether these patterns of regional precipitation and temperature change could be reproduced in the Mid-Pliocene without prescribing a permanent El Niño-like state.

With fixed SSTs in the Pacific, it was possible to examine whether any of the regional temperature and precipitation patterns could be reproduced independently of a warming in the EEP. The results show that, for some areas, this is possible, with temperature patterns over North America and Japan, and both the SAT and precipitation patterns over South America resembling the regional changes that occur in these regions during a modern El Niño.

Adding ENSO variability and a mean SST warming in the EEP (Plio\(^{\text{Control}}\)) strengthened the signals noted in Plio\(^{\text{Fixed}}\), and reproduced many of the other regional climate patterns identified in the Pliocene proxy data (table 1), previously attributed to a permanent El Niño state. Comparing these results with a simulation prescribed with a permanent El Niño condition, i.e. a time-invariant pattern of warmer SSTs in the EEP (see fig. 1 in Haywood et al. 2007), showed no significant differences between the temperature and precipitation patterns observed, although the signals were stronger. This suggests that although a similar mean climate state is reproduced that today reflects El Niño conditions, it may be a result of other factors in the Mid-Pliocene.

The next set of simulations examined this possibility further, focusing on the regional patterns of change and their association with alterations to the model boundary conditions. Starting with the pre-industrial climate (PreInd\(^{\text{Coupled}}\)) and moving to the Mid-Pliocene, the vegetation, orography, ice sheets and atmospheric CO\(_2\) concentration were altered in a series of incremental steps (table 3). Some regions, such as over northwest Canada, have shown climate patterns similar to those seen during a modern El Niño over most of the experiments, while other areas have SAT and precipitation patterns that become stronger after specific boundary conditions are altered (i.e. over South America).

Many of the temperature and precipitation patterns seen in the results became more apparent once the orography was amended. This included a large impact on local climate, i.e. temperatures over North America increased by up to 4°C and...
precipitation up to 2 mm d\(^{-1}\), as well as affecting a wider geographical area, via feedbacks that arise through changes in atmospheric circulation. The effects of altering the ice sheets had little impact on the precipitation patterns, and were generally constrained to changes in SATs in the high latitudes through ice-albedo feedbacks. The largest impact was observed after altering the atmospheric CO\(_2\) concentration, which has a global distribution; hence, the radiative forcing resulting from this change would also be global, compared with the more regional effects of vegetation, orography and ice sheets.

However, not all of the temperature and precipitation patterns associated with a modern El Niño and shown in the Pliocene proxy data have been replicated in the Mid-Pliocene simulations. For example, over the Gulf of Mexico, our results show warmer temperatures and reduced precipitation, particularly over the east coast, instead of the pattern of decreased temperature and increased precipitation that occurs during a modern El Niño and is present in the proxy data listed in Molnar & Cane (2002). As the rest of the Pliocene proxy data can be likened to the model results in many of the locations shown, this area stands out as an anomaly.

This can partly be explained by examining more closely the data cited by Molnar & Cane (2002). Although the regional climate trend over the Gulf of Mexico during a modern El Niño is to become cooler and wetter, the supporting Pliocene data for this region were obtained from only three points, located at Veracruz, Mexico (Graham 1989\(a,b\)), Beck Ranch, Texas (Thompson 1996) and around Miami (Cronin & Dowsett 1990).

Although the data from Thompson (1996) indicate a wetter climate in this area during the Pliocene, the source of the data (Texas) is located in a region where our model results also show higher precipitation. The Mid-Pliocene simulation therefore matches the proxy data used in Molnar & Cane (2002) quite well, but does not show the band of increased precipitation in the observed data that extends to the east coast of America during a modern El Niño. The distribution of SAT anomalies in the model is slightly less well correlated with the observed ENSO teleconnection patterns, with higher temperatures still observed over Florida and Mexico (figures 4 and 5), while the proxy data (Graham 1989\(b\); Cronin & Dowsett 1990) indicate reduced temperatures at these locations (on average 2\(^\circ\)C lower). This pattern of cooling, however, is not replicated even with a permanent El Niño condition prescribed in HadCM3 (see fig. 1 in Haywood et al. 2007), suggesting that another factor is causing this pattern to exist.

A new vegetation reconstruction for the Piacenzian Stage, from global palaeobotanical data, has been presented in Salzmann et al. (2008), which shows little definitive evidence of terrestrial vegetation indicating cooler or warmer temperatures around the Gulf of Mexico. Over Florida and the southernmost regions of North America, for example, warm-temperate conifer forests suggest temperatures during the Pliocene similar to those seen today (e.g. Willard et al. 1993). Willard et al. (1993) produced results for the Mid-Pliocene that showed that SSTs and SATs in subtropical Florida were close to today’s temperatures, although the difference between present-day and Mid-Pliocene temperatures increased poleward (Willard et al. 1993). The marine ostracode assemblages from sites around Florida and the southeastern states, which show this area to be 1–2.5\(^\circ\)C cooler than today (e.g. Cronin & Dowsett 1990; Cronin 1991), are from

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shallow water sites (Molnar & Cane 2007) and may be more representative of the regional oceanographic setting as opposed to a result of a warming in the EEP. The lower temperatures seen may be indicative of cool, deeper upwelled water (Allmon 1993; Williams et al. 2009).

5. Conclusions

This paper discusses the mean climate state of the Pliocene and determines whether it could be a result of a permanent El Niño condition as has previously been suggested. With the exception of the Gulf of Mexico, the results presented show that it is possible to reproduce the regional temperature and precipitation patterns associated with a modern El Niño in the Mid-Pliocene without the existence of a permanent El Niño or, in some cases, without any SST warming in the EEP at all (Plio$^{\text{FixedSST}}$). Not every aspect of the Mid-Pliocene climate that differs from modern conditions can therefore be explained as a response to a warming in the EEP (Molnar & Cane 2007), and the regional climate patterns seen, which today are associated with an El Niño event, may be a result of other processes, highlighting the importance of equifinality. Nevertheless, the results do not rule out the possibility that the Pliocene ocean–atmosphere system may have been in a permanent El Niño state (within the confines of the definition used here), and more studies are required.

Further modelling studies are required to investigate the uncertainties in model–data comparisons. Although the model simulations for the Mid-Pliocene have been able to replicate most of the climate patterns seen in the observed and proxy data, some significant differences remain in areas where the spatial and temporal resolution of the data is perhaps not high enough to validate the model, instead providing only a reconstruction of mean climate conditions. Higher resolution proxy data would improve our understanding of the regional patterns seen in the Pliocene. There is a clear pattern of ENSO variability shown in Mid-Pliocene coupled ocean–atmosphere model simulations (e.g. Plio$^{\text{Control}}$; see fig. 1 in Haywood et al. 2009), which presents a challenge to the geological community to determine whether the same can be found in the sedimentary and proxy record in general.

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