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Interannual climate variability seen in the Pliocene Model Intercomparison Project

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Abstract

This document lays out the response to the Reviewers' and Editor's comments. I will tackle a couple of overarching themes first.

1 Combined Responses

1.1 Significance

Both reviewers made comments about the statistical significance of the results. I'd wondered about that myself and had tried to address it in the original manuscript. I have since decided to create a new section devoted to the topic in the revised manuscript. I had intended to apply the method of Stevenson et al. (2010) to estimate the individual ENSO changes. However, after a frustrating couple of days grappling with errors in their Matlab codes and an abortive attempt at rewriting them in NCL, I had to give up on it. In the revised manuscript I do, however, stress that I can not be completely sure that this is a real result, until someone finds a plausible reason for it.

> **Reviewer One:** When I started reading this, I wondered how likely it was to see a coherent shift in just one of the metrics considered. I note that this is discussed later in the paper, but my own calculations differ from those of the author: 8/9 of the models go in the same direction. I calculate that the chances of this are 1 in 2^6 = 1/64. There are many MIPS, so maybe not surprising that one of them shows a 1/64 response!! Also, many indices are inspected here the chances of at least one of them showing a significant trend across several models is not actually that small! If a physical mechanism is identified that could explain the signal seen, then this would be more acceptable, but without a physical mechanism one is left wondering how much is just random variations!

As I see it, there are three individual points being made in this comment. Firstly, that calculating the probability is itself ambiguous. Secondly, that I should flag the discussion of the significance earlier in the manuscript. And thirdly, that without a physical mechanism, one should be sceptical of the result. I believe I have now addressed these points in the new section devoted to significance. In the introduction, I explicitly mention the existence of this section and I have also highlighted it in the conclusions. Incidentally, I should also mention the Reviewer One has subsequently revised his estimate of the probability.

> **Reviewer Two:** Several of the models represented in this study have long preindustrial controls in the CMIP5 database. The robustness of the conclusions should be strengthened by calculating the ranges of interannual variability of ENSO, IOD, and PDO for such models, subsetting their entire time series for the different shorter segment lengths available in the PlioMIP database.

I agree this is the ideal method of computing the significance. However, the models with the long pre-industrial control simulation only have a thousand years or so in the CMIP5 database. This will not create sufficient 200 year-long subsets for adequate significance testing. Nonetheless I take the spirit of the comment to suggest that I should have been clearer about the statistical significance of the results. In the new 'significance' section, I describe the issue above.

> **Editor:** Ultimately it would lead to a far more satisfying and reassuring conclusion if the cause of the consistency in modelled ENSO behaviour for the Pliocene could be identified rather than simply speculated.

This is clearly the case, and I feel sceptical about the significane of the response myself (which is why I had included my initial estimate of the probability). I have now stated this explicitly at the end of the significance section and revised the conclusions.

1.2 Authorship

> **Reviewer One:** My understanding is that at one of the PlioMIP meetings, there was an agreement that any paper which used as-yet-unpublished model outputs,

would include as co-authors those members of PlioMIP who had produced the model outputs. As such, I was surprised that this was a single-author paper, because as far as I am aware, the variability in the model SST fields has not previously been published.

Editor: Authorship of PlioMIP Papers was discussed at the 2011 PlioMIP workshop in Reston USA. The reviewer is correct that the anticipated norm is for appropriate representatives of each modelling group to be approached and offered co-authorship on papers that use their model outputs. Time series SSTs necessary for the evaluation of ENSO have not been included in other papers, nor have ENSO analyses been presented consistently, therefore this paper would seem to fit into the category where co-authorship should be offered. However, following the 2011 workshop no one came forward to complete the ENSO analysis and the author has therefore filled an important gap in the PlioMIP Phase 1 science portfolio. As the editor and lead on PlioMIP modelling I would not personally hold the author to the Reston 2011 agreement. However, I think it would be best practice to talk to representatives of each modelling group anyway to ensure that the summary of ENSO behaviour for each model presented in the paper in in accord with the understanding of ENSO behaviour for the Pliocene within each modelling group. This is valuable especially given the stated potential for different analyses facilitating different interpretations of the result. That may provide sufficient intellectual input for the author to feel able to offer co-authorship anyway.

I was not initially aware of this agreement, although it does explain the authorships of the first batch of the PlioMIP papers that I edited for the Climate of the Past special issue just before the IPCC deadline. I actually questioned Ran Zhang about it, as I felt that with so many English-speaking authors the manuscript language should have been more readable. Several of the modelling groups have already described the ENSO time series (NCAR, NorESM and FGOALS), although clearly most have not.

I have since spoken with representatives of over half of the groups about it (mainly over my Poster at AGU). Not one of them raised any expectation that they would be included as a author to the manuscript, nor any objection when I brought the topic up. Most surprisingly at that meeting, Axel Timmerman suggested that COSMOS ENSO is atrocious because of its grid. He suggested that the reason I could not find any documentation of its preindustrial was that no-one has published on it yet.

To sum up, I would like to keep this manuscript as a sole author one. I don't feel this would be detrimental to the spirit of the PlioMIP exercise, which I want to support and encourage.

2 Reviewer Two

> 1. Nino3.4: The common index for Nino3.4 is its standard deviation rather than its variance. See for example, the IPCC AR5 WG1, Chapters 9 and 14. The author should justify why presenting variance is a better metric for the Pliocene. Otherwise, I would recommend using the standard Nino3.4 index to make the results more relevant to future projections.

This change has now been implemented throughout the revised document.

> How are grid cells with sea ice present handled when calculating the first EOF of the North Pacific (20-70N) SST? Does this affect the outcomes?

I do not think this issue will impact the outcomes in this context. I have chosen not to describe this technical point explicitly in the manuscript as it was already on record in the interactive discussion - wherein I state "The Pacific Decadal Oscillation is calculated as the EOF of the sea surface temperatures in the North Pacific; the poleward portion of which would be covered in sea ice during the winter months (at least in the preindustrial). The ocean covered with sea ice records a surface temperature of -1.8 C, and therefore the variability in the winter months will be suppressed. I do not think this is an issue for diagnosing the PDO in the simulations presented here. The sea ice retreats in the Pliocene simulations leading to less SSTs suffering from this suppression. Inspection of the PDO patterns shows that all their centres of actions are off the coast of Japan and compare well with the observed pattern."

3 Reviewer One

I will outline my response to nearly all the points revised by Reviewer One individually below.

> P3788 mentions reduced gradients, but should reference current discussion of how robust this is – see O'Brien et al (2014) and Pagani (2014).

Personally, I have some issues with that work and have a Correspondence (and Reply) working its way through Nature Geoscience. However, I don't necessarily see my reservations and that discussion are too relevant here, as they are just describing the motivation for previous work looking at ENSO in the Pliocene.

> P3789, line 20 Zhang et al. (2012b) posit an elegant solution to these questions. Not clear what 'these questions' actually are.

I have rephrased this sentence.

> Bonham (PhD thesis, University of Leeds) carried out a rather extensive study of ENSO in the mid-Pliocene – would be worth citing their findings and explaining how your work builds on their work.

I was not aware of this component of Sarah's work before. I have now read it and discussed her results in the pertinent section. I am confused in they do not give the same direction change as the HadCM3 run analysed. I presume the difference occurs due to the PRISM3 orography, but it could also tie into Reviewer Two's comments about significance.

> It is not clear if the lengths of the simulations given are the entire model simulations length, or the length of the analyses. The table should include the length of the whole simulation as well as the analyses.

I have retitled the table to make it clearer that this is length corresponded to number of years analysed. I have chosen not to give the full length of the simulations as I do not think they bear much relevance to the conclusions. The table is already a little too large.

> P3791, line 19. Need to define N3 and N4, before defining Nct and Nwp.

These were defined in the previous sentence of the original manuscript. I have not changed them.

> P3791, line 25. Is the 5-month smoothing really a 5-year smoothing, if SSTA is defined for each month? This section would probably benefit from some equations.

The Trenberth (1997) method does advocate a 5-month smoothing, so as to not declare an El Niño off the back of a single warm month. I beg to differ about the inclusion of the equations, as I feel that unnecessary equations can put-off readers.

> P3792, line 22. (Visualisation of SST time series would be normalised solely by the preindustrial standard deviation). Not sure what “Would be” means here. Would if what?

This point is only incidental to the manuscript, so I have removed it completely.

> Section 2.2. The analysis is described in words, but many aspects would benefit from equations, e.g. Lanzcos low-pass filter, Dipole Mode index, PCA, smoothed and tapered periodogram.

All of these terms are pretty standard techniques and I have been using the standard definitions. I do not feel it necessary to describe them. I will post the NCL code onto the PlioMIP data server, so that those who are really interested can inspect it and access the post-processed SST indices. I hope that will suffice.

P3793, line 16: “each property is investigated independently of the others.”. Not sure what this means.

The advantage of the approach I have followed is that changes in amplitude will not impact changes in period or structure. This is not true for most analyses and leads to additional confusion in their interpretation (for example a reduced amplitude will be visible as reduced spectral power at all frequencies). I have refined the text in an attempt to make this clearer.

P3793, line 18. reference Figure 1a here. Give 4 panels in figure 1 names (a,b,c,d) and reference the individual panels.

Individual panels have now been labelled in every single figure and figure 1a is reference as suggested.

P3793, again, give some equations to define the 4 “moments”.

I feel it would be more confusing to provide the equation of, say, a mean, than just to state it in the text. In part, because readers will feel that I have done something out of the ordinary to require explaining by the equation, when this is not the case.

P3794, line 21-26 – somewhat confusing section.

I have attempted to refine this section of text a little.

P3795, line 10. Not sure what the “ensemble average power spectrum” really means. Is it meaningful to average power spectra? Or is it the spectra of the average variability? (maybe even less meaningful!).

I believe it is meaningful to average the power spectra. Certainly it is clearer than showing 18 different power spectra together. An & Choi (2010) provide a nice example of this metric’s utility, whihc I now reference in the text.

Figure 3 – ensemble average structure is discussed, but is there any change in structure for any ensemble member?

Not really. I have now added a sentence to state this explicitly.

Figure 4 – is “change in variance” Plio-Preind or Preind-Plio?

I have altered the figure caption to make this clearer.

P3796, line 26 – I would contest that these runs are ‘in equilibrium’.

This is a fair point, and I have added in the word ‘closer’ to indicate the relative sense of this compared to future projections.

P3797, line 8 – typo ‘referred as to’.

Corrected

P3797, line 22 – ‘Because of potential model biases, the most appropriate mode is determined from visual comparison of the model-derived EOFs to those found from the detrended ERSST observations.’. Not sure what this means – what is ‘appropriate’ and how is this found from a ‘visual comparison’.

I have rephrased this sentence. I hope this will make it clearer.

P3799, line 6 – typo ‘cycle that’ to ‘cycle than’

Corrected

P3800, line 4 – this seems a bit of a cop-out! Many studies explore modern ENSO teleconnections and I don’t see why a similar analysis could not be carried out here. It would be of considerable interest!

Unfortunately the data needed to do this isn’t available for all the models on the PlioMIP server. I now state that in the manuscript.

> P3800 top – not sure I agree with this probability! Especially as so many metrics were examined (see earlier comment).

See response section on Significance above.

> P3801 – Bonan et al carried out a factorisation which partitioned possible changes into either CO2, orography, ice, or vegetation. Their work may give some insights to the causes of change?

I wasn't aware of this work before it was mentioned by the reviewer. I now discuss it's relevance.

> P3802 top – again, 'observed' pliocene W-E gradient is equivocal, O'Brien et al.

I have removed the word 'observed' and replaced with 'range of reconstructed'. Irrespective of my opinions of on the O'Brien et al. results, it's clear there is uncertainty in the reconstructions which I hadn't acknowledged here.

4 Editor

> The PhD work of Bonham utilised the PRISM2 data set of boundary conditions. The major difference compared to PlioMIP was the specification of a lower cordillera of North and South America in PRISM2 compared to PRISM3/PlioMIP (by 50%). That provides a possible explanation to the differences noted with the work of Bonham and it would be useful to explore this further within the paper. I will send the author a copy of the relevant thesis.

Thank you very much for this. I have now digested the results, which do not fit with the response seen by the version of HadCM3 seen in this ensemble. I now use this to speculate that the plausible mechanism really does lie in the orographic forcing. Perhaps this means the consistency will disappear in the next generation of PlioMIP.

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Abstract

Following ~~proxy observations of~~ reconstructions suggesting weakened temperature gradients along the Equator in the early Pliocene, there has been much speculation about Pliocene climate variability. A major advance for our knowledge about the later Pliocene has been the coordination of modelling efforts through the Pliocene Model Intercomparison Project (PlioMIP). Here the changes in interannual modes of sea surface temperature variability will be presented across PlioMIP. Previously model ensembles have shown little consensus in the response of the El Niño–Southern Oscillation (ENSO) to imposed forcings – either for the past or future. The PlioMIP ensemble, however, shows surprising agreement with eight models simulating reduced variability and only one model indicating no change. The Pliocene's robustly weaker ENSO also saw a shift to lower frequencies. Model ensembles focussed at a wide variety of forcing scenarios have not yet shown this level of coherency. Nonetheless the PlioMIP ensemble does not show a robust response of either ENSO flavour or sea surface temperature variability in the Tropical Indian and North Pacific Oceans. Existing suggestions of ENSO properties linked to changes in zonal temperature gradient, seasonal cycle and the elevation of the Andes Mountains are investigated, yet prove insufficient to explain the ~~coherent~~ consistent response. The reason for this surprisingly coherent signal warrants further investigation.

1 Introduction

The Pliocene is an interesting time period for palaeoclimate research. It was the last time that atmospheric carbon dioxide concentrations were similar to their present, elevated values (Masson-Delmotte et al., 2013; Fedorov et al., 2013). Sea surface temperature estimates from geochemical proxies indicate that the Tropical Pacific saw reduced zonal (Wara et al., 2005) and meridional temperature gradients (Brierley et al., 2009) in the Early Pliocene. The gradient developed as time progressed, but was still significantly reduced by the mid-Pliocene (Dowsett et al., 2012). These reduced temperature gradients are thought to have consequences for the climate variability of the period. Most discussions have centred on the behaviour of the El Niñ~~o Southern~~ o–Southern Oscillation (ENSO) – an interannual mode of climate variability whose warm, El Niño phase has been used to help visualise a world with reduced zonal temperature gradients (e.g. Fedorov et al., 2006).

Efforts have been made from both the ~~observational~~ data and modelling sides to understand the relationship between the reduced zonal temperature gradient in the Pliocene and ENSO. Watanabe et al. (2012) and Scroxton et al. (2011) present geological evidence for the existence of ENSO variability, whilst Watanabe et al. (2012) go further and suggest that any changes in period cannot have been too great. The idealised model study of Fedorov and Philander (2001) anticipates weaker ENSO amplitude with a weaker sea surface temperature (SST) gradient, whilst von der Heydt et al. (2011) disagree. Both Haywood et al. (2007) and Fedorov et al. (2010) simulate an extant ENSO in coupled climate models with reduced zonal SST gradients. Manucharyan and Fedorov (2014) manipulate the zonal SST gradient in a coupled climate model and describe a non-linear dependence of the climate variability on the resultant state. It has not yet been possible to drive substantial alterations in the Pliocene zonal SST gradient through a physically plausible mechanism that does not involve modifications to the fundamental physics in a climate model.

Zhang et al. (2012b) ~~posit an elegant solution to these questions by describing the tropical climate of a~~ investigate the ENSO and mean equatorial SST gradient in one simulation performed as part of the Pliocene Model Intercomparison Project (PlioMIP) with standard model physics. They found that the NorESM-L model (Table 1) simulates a reduction of zonal SST gradient as well as a weakening of ENSO amplitude when forced by mid-Piacenzian boundary conditions. Here I describe the climate variability of all the model simulations that were performed as part of the same PlioMIP ensemble. In part, this work is motivated by a desire to explore whether this result holds across the ensemble; in part by academic curiosity about past climate variability.

The remainder of this article will first give a brief overview of the PlioMIP ensemble (Sect. 2.1) and detail the data analysis methods used (Sect. 2.2). The results section will describe Pliocene climate variability in the Tropical Pacific (Sect. 3.1), Indian (Sect. 3.2) and

North Pacific (Sect. 3.3) oceans. I will then discuss the ~~implications~~ significance, statistical (Sect. 4.3) and otherwise, of these results and attempt to provide an explanation for them.

2 Methods

2.1 PlioMIP

The PlioMIP ensemble has been created to investigate the climate of the warm mid-Piacenzian. Here, I utilize only the contributions to experiment 2 which requires the use of coupled climate models (Haywood et al., 2013). Nine climate models from different institutions around the world have contributed simulations to the project (Table 1). Each model has performed a preindustrial simulation following the CMIP5 protocol. They also perform a simulation representing the average interglacial conditions between 3.264 to 3.025 million years ago (Haywood et al., 2011). This involves increasing the carbon dioxide concentrations (278 to 405 ppm) and altering the prescribed boundary conditions in line with the Pliocene Research Interpretation and Synoptic Mapping reconstructions (PRISM; Dowsett et al., 2012). A full description of the PlioMIP experiment protocols are given by Haywood et al. (2011) and the implementation of them for each model is given by the accompanying reference in Table 1.

The simulations in the PlioMIP ensemble have been previously investigated. As well as each of the single model descriptions (listed in Table 1), there have been coordinated studies across the whole ensemble. The large-scale features of the ensemble are described in Haywood et al. (2013). The simulations warm between 1.8 and 3.6 °C on the global mean. Two of the individual model papers describe aspects of the climate variability (Rosenbloom et al., 2013; Zheng et al., 2013). Additionally Zhang et al. (2012b) focus specifically on the ENSO simulation of NorESM-L. They find substantially weaker variability in the Niño 3.4 region, which they associate with the reduced equatorial SST gradient in the Pliocene simulation. An analysis of the climate variability across the PlioMIP ensemble using an unified methodology has not been previously performed.

2.2 Data ~~analysis~~Analysis

Many differing approaches have been devised to study climate variability. Two distinct techniques to detect modes of variability are followed here: principal component analysis and index-driven metrics. Both techniques involve computing the average annual cycle and looking at anomalies from that. The lengths of records archived in the PlioMIP database is at best 200 years of sea surface temperatures; at worst 100 years are available (see Table 1). As these time series represent "equilibrium" states from the end of long simulations, they should have quasi-stable climates. The annual cycle was computed as the average of the whole available record for each model grid point and month of the year. Sea surface temperature anomalies (SSTA) from this annual cycle were computed.

The area-weighted average SSTA were computed over several standard regions. The Niño 3.4 region is used for the majority of the analysis, which is defined as 170–120° W, 5° S–5° N. Niño 3 (150–90° W, 5° S–5° N) and Niño 4 (160° E–150° W, 5° S–5° N) were also computed. They show similar response to the Niño 3.4 indices, so the following will concentrate on it. However, Ren and Jin (2011) devised a simple transformation of the Niño 3, N_3, and Niño 4, N_4, regions to track two different types of ENSO. These are discussed further in Sect. 3.1.4. This transformation creates two new indices, N_{CT} and N_{WP} characterising the cold tongue and warm pool types of El Niño respectively (Eq. (1); Ren and Jin, 2011).

$$\begin{cases} N_{\mathrm{CT}} = N_3 - \alpha N_4 \\ N_{\mathrm{WP}} = N_4 - \alpha N_3 \end{cases} \qquad \alpha = \begin{cases} \frac{2}{5}, & N_3 N_4 > 0 \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

Trenberth (1997) advocate using a 5 month running window to smooth ENSO SSTA indices. Some ensemble members exhibit high sub-seasonal variability (e.g. NorESM-L; Zhang et al., 2012b). Also the normalisation (described below) of the power spectra would be distorted by variations in the annual cycle. Therefore, smoothing is instead performed with a Lanczos low pass filter of eighteen months (UCAR, 2014).

The Dipole Mode Index is used to look at Indian Ocean variability (Saji et al., 1999; Cai et al., 2013). It is defined as the difference between area-weighted average temperature anomalies between the West (50–70° E, 10° S–10° N) and the South East (90–110° W, 10–0° S) Indian Ocean.

An alternate approach to define the Indian Ocean Dipole is as the second Empirical Orthogonal Function (EOF) of the Indian Ocean between 20° S and 20° N (Deser et al., 2010). Principal component analysis is used to compute the EOFs from the unsmoothed sea surface temperature anomalies using an area-weighted covariance approach (UCAR, 2014). The first two EOFs of the Tropical Pacific (140° E–80° W, 15° S–15° N) and North Pacific (110° E–90° W, 20–65° N) are also computed along with the global patterns. Power et al. (2013) found a robust future change in the ENSO structure by creating ensemble averaged EOF patterns. To facilitate this, the EOFs are computed on their native grid and then bilinearly interpolated onto the $2^\circ \times 2^\circ$ grid of the ERSST observations (Smith et al., 2008). The EOF patterns are then normalised by the spatial standard deviation of the region (Power et al., 2013).

Spectral analysis is used to ~~analyse~~ investigate the frequency properties of the inter-annual variability. The power spectra are computed from a smoothed and tapered periodogram (UCAR, 2014). To isolate the temporal properties from any amplitude changes, all time series are normalised by their own standard deviations. ~~(Visualisation of SST time series would be normalised solely by the preindustrial standard deviation, as in Zhang et al. (2012b) , to retain changes in amplitude.)~~ This applies to both the SST indices and the principal components, both of which are low pass filtered at 18 months (as described above) to avoid signatures associated annual cycle changes. The dominant period (as shown in Tables 2 and 3) is defined as the period with the maximal power density in the spectrum. Ensemble average spectra are computed after this normalisation.

3 Results

3.1 Tropical Pacific

The most well studied mode of interannual climate variability is the El Niñ~~o Southern~~ o–Southern Oscillation (ENSO). However, this does not mean it is yet well understood. Future projections of ENSO are model-dependent – with some models showing increasing variability and others showing reductions (Collins et al., 2010). There are a plethora of metrics and approaches to investigate how well models simulate the present-day properties of ENSO. Novel approaches have started to focus on the underlying physical processes, rather than the emergent climate variability that will be the focus of this work (e.g. Jin et al., 2006). The model representation of ENSO has improved in the CMIP5 compared to CMIP3 (Bellenger et al., 2013) with more models showing a realistic power spectrum (Flato et al., 2013). Power et al. (2013) was able to show the benefit of separating the various of aspects of ENSO during model intercomparison by finding a robust pattern of change in 21st century simulations. Motivated by this result, combined with the fact that the PlioMIP models show a large diversity of ENSO simulation quality, each property is investigated independently of the others. The method described above isolates the amplitude, frequency and structure. This means that say the reduction in amplitude noted by Zhang et al. (2012b) will not interfere with the spatial pattern associated with an El Niño. Using a composite El Niño approach with a predefined threshold instead (e.g. Haywood et al., 2007) in that situation would only pick up fewer, stronger El Niños which may themselves have a different structure (Ashok et al., 2007).

3.1.1 Moments

The quality of the ENSO representation varies across the ensemble ~~.~~ (fig. 1a). COSMOS has substantially more variability than seen in observations (over six times as much as seen in ERSST). In this particular model, it is probably related to the excessive seasonality of an extensive cold tongue. Conversely, MIROC4m has only half as much variance as seen in observations. It is also worth pointing out that where the model versions have been include in the CMIP3 or CMIP5 ensembles, the statistics computed do not exactly match those of Bellenger et al. (2013). I suspect this arises predominantly from the shorter lengths of the preindustrial controls simulations analysed here (which have been chosen to correspond to the Pliocene data length where possible), with some contribution from the 1.5 year low-pass filter applied here. These differences do lend a cautionary aspect as they highlight the centennial scale variability in ENSO characteristics (Wittenberg, 2009) that could confound the results shown here.

The variance is the most discussed moment as it is a valuable metric for the amplitude of the Niño 3.4 distribution(although sometimes its square root is used instead such as by Taschetto et al., 2014) . . Here I will follow the conventional approach of presenting the standard deviation instead (e. g. Taschetto et al., 2014) . There is a near unanimous weakening ENSO amplitude in seen in the mid-Pliocene simulations (Fig. 1a). The lone dissenting model is MRI, which itself shows no change. The ensemble average variance standard deviation in the mid-Pliocene is roughly two-thirds the variance only 80% of the amplitude in the preindustrial control simulation (Fig. 1b; Table 2).

A less coherent pattern comes from looking at the higher moments of the distribution. It is observed that El Niños are generally stronger than their La Niña counterparts – equivalent to the Niño 3.4 distribution having a positive skew. This property is captured by two thirds of the ensemble members in the preindustrial conditions. However the ensemble is equivocal about changes in skew for the Pliocene simulations (Fig. 1c). The kurtosis is a measure of spread of the distribution compared to a Gaussian. A positive kurtosis means more of the activity occurs near the mean (zero by definition in this case) rather than out in the tails. Again there is little consistency across the ensemble as to the change in kurtosis (Fig. 1d).

These moments can combine to define other possible descriptions of ENSO. are common, generic descriptors of distribution, but clearly other features of a distribution may also be worthy of investigation. One such features of potential relevance in a climate is looking at the nature of the most extreme events at the far end of the tail. For example, Cai et al. (2014) detect an increase in intensity of the strongest El Niños in future simulations across most CMIP5 ensemble members, despite little agreement on trends in the moments investigated here. Their analysis looked at precipitation where this feature has oft been noted before such as in the hydrological cycle (Collins et al., 2013) and tropical cyclones (Knutson et al., 2010). Nonetheless it is not implausible for increasing skew or a reduction in kurtosis to alter the tail of the Niño 3.4 SST distribution, such that more intense El Niños would be seen despite a reduction in variance overall.

3.1.2 Frequency

The only observational evidence of ENSO properties in the Pliocene relate to its frequency (Watanabe et al., 2012). Therefore the simulated changes in the frequency are studied in isolation. This is achieved by normalising the time series by their standard deviations (Sect. 2.2). This then allows the individual power spectra to be averaged across the ensemble (Fig. 2). The power at the annual and sub-annual period have been removed through the data analysis (Sect. 2.2; unlike An and Choi, 2013).

Eight of the nine models show the dominant period of Niño 3.4 SSTA becoming longer; only COSMOS exhibits a shift to a shorter period (Table 2). This behaviour is also shown in the ensemble average power spectra ~~(Fig. 2).~~ (Fig. 2, see An and Choi, 2013, for discussion of this approach) . Both these spectra exhibit two peaks at around 3 years and a stronger one at lower frequencies. The lower frequency peak shifts substantially to longer periods, the significance of the smaller shift in the 3 year peak is debatable. A coherent lengthening of ENSO period is not robustly detected in future simulations. An and Choi (2013) notice a lengthening for the mid-Holocene, but only with the PMIP2 generation of models not for PMIP3.

3.1.3 Structure

The conventional approach to investigate changes in the SST pattern associated with an El Niño involve compositing of the events above a certain threshold (e.g. Haywood et al., 2007). I aim to study changes in the structure climate variability patterns in isolation from any changes in amplitude or period, both of which show a robust Pliocene response individually. This is achieved by following the methodology of Power et al. (2013) through EOF analysis and normalisation. For each model, the first EOF of the Tropical Pacific is significantly correlated to the Niño 3.4 ($P < 0.05\,\%$). The first EOFs of the ensemble explain on average 60 % of the Tropical Pacific variance in the preindustrial simulations compared to 56 % of the variance in the Pliocene simulations on the ensemble average.

The structure of ENSO is predominantly similar in the two time periods (Fig. 3). There is a shift towards the warmth of an El Niño expanding expadning further across the Tropical Pacific. Statistical significance with such a small ensemble is hard to compute . (Sect. 4.3). Instead a simpler measure of coherency is used – a location is considered coherent if more than seven of the nine models show a response in the same direction (Fig. 3). None of the individual models show substantial changes in their ENSO structure (not shown).

3.1.4 Flavour

A recent development has been the identification of two types of El Niño (Ashok et al., 2007), which probably represent end members from a range of behaviour. A variety of approaches exist to detect and disaggregate the two different flavours. For ease of computation, I opt for the technique of Ren and Jin (2011, Eq. 1). The variances of the cold tongue and warm pool types of ENSO show a large spread in quality of their simulation compared to observations (Fig. 4a). This is also true of the wider CMIP5 ensemble (Taschetto et al., 2014).

The ensemble shows no robust change between the variances of the two flavours (Fig. 4b-d). Instead the reduction in amplitude effects both flavours (only MRI-CGCM2 shows an increase in either form and even that is minimal). Both HadCM3 and NorESM-L switch the dominant flavour in the mid-Pliocene, but in opposite directions. An alternate method to address the same question is to analyse the second EOF of the Tropical Pacific. This also shows little coherent shift (not shown).

3.1.5 Summary

~~To summarise, the~~ The PlioMIP ensemble is remarkable amongst climate ensembles in that it shows a consistent message about changes in ENSO properties. ENSO in the Pliocene is simulated to have been weaker and less frequent. Changes in structure and flavour are less coherent however. The reason why the PlioMIP ensemble shows a signal, whilst other ensembles do not, is unclear. Compared to CMIP5 future scenario ensembles, this one has been run closer to equilibrium and has longer time series to analyse. However, that cannot be sufficient as other ~~equilibrium~~ palaeoclimate ensembles do not see robust responses – for example the mid-Holocene (An and Choi, 2013) and the Last Glacial Maximum (Zheng et al., 2007).

3.2 Tropical Indian variability

Climate variability in the Tropical Indian Ocean has strong links to that in the Pacific, in part through their sharing of a single warm pool. The leading mode of Indian Ocean temperature variability is therefore a corollary to ENSO, although it is sometimes referred ~~as to~~ to as the Basin Mode (Deser et al., 2010). Around the turn of the century an additional mode of variability was identified – the Indian Ocean Dipole (IOD, Saji et al., 1999). The Indian Ocean Dipole can sometimes track ENSO, yet sometimes operate in isolation. It manifests through changes in the zonal gradient of the Indian Ocean and can be tracked by the Dipole Mode Index (DMI, Saji et al., 1999, Table 2). The quality of the preindustrial simulation of the Dipole Mode Index varies across the ensemble; as it does in the wider CMIP5 ensemble (Weller and Cai, 2013). Whilst several of the ensemble members show a change in amplitude of the Indian Ocean Dipole, there is no consensus in their sign (Table 2). The detection of a coherent signal may be hampered by biases in the climate models meaning that the DMI is not capturing the centres of actions of the Indian Ocean Dipole.

An alternate approach is to use principal component analysis to detect the Indian Ocean Dipole. A conventional methodology is to label the first EOF as the Basin Mode and the second EOF as the Dipole Mode (Deser et al., 2010). ~~Because of potential model biases~~

~~, the most appropriate mode is determined from visual comparison of~~ Model biases mean this may not always be the correct; for example both of first two EOFs of HadCM3 show a basin-wide pattern. Therefore, visual inspection is used to categorise the nature of each the model-derived EOFs in comparison to those found from the detrended ERSST observations. The results of this analysis is shown in Table 3, along with both the ~~variance and~~ percentage variance explained by it and the dominant period of the accompanying principal component timeseries. It is hard to pull out a coherent message about Pliocene Indian Ocean variability from this ensemble. Although it is interesting to note the potential for a change in the relative strengths of the two modes – as seen by CCSM4 for example (Table 3).

3.3 North Pacific variability

The dominant form of sea surface temperature variability in the North Pacific is a low frequency mode termed the Pacific Decadal Oscillation (PDO, Mantua et al., 1997). The centre of action of this oscillation is the Kuroshio Extension around 40° N, although it has significant impacts remote from this region. The connection between the PDO and low frequency variations in ENSO is complex. Here, I follow Deser et al. (2010) and define the PDO as the first EOF of the North Pacific (20–70° N). The EOF patterns are again normalised by their spatial standard deviations, however in this instance both simulations are normalised by the preindustrial value. This retains information about the relative amplitude of the mode in the principal component time series. The ~~variances~~ standard deviations of the PDO timeseries are shown ~~in~~ (Fig. 5a), along with the percentage change ~~.~~ (Fig. 5b). There is little consistent response of the PDO amplitude to the imposing of the Pliocene conditions. The same is also true of the frequency and structure of the PDO when studied in isolation (not shown).

4 Discussion

Climate variability in three regions of the global ocean have been investigated in the PlioMIP ensemble. The nine constituent models often are equivocal about the changes in climate variability that might have occurred in the Pliocene. However, for the two most studied facets of the dominant mode of variability, they provide a coherent message: Pliocene ENSO was weaker and less frequent.

This raises three questions: (a) how does this response fit with the geological evidence (b) ~~did~~ can ENSO become so weak that it ~~lost~~ loses its global reach, and (c) ~~why does the PlioMIP ensemble show this response~~what can explain the response of the PlioMIP ensemble?

4.1 Observations

Observational evidence for Pliocene climate variability is sparse. Hill et al. (2011) discuss changes in the Northern Annular Mode; something not analysed here. Scroxton et al. (2011) use the distribution of single foraminifera in the Eastern Equatorial Pacific to infer the presence of ENSO in the Pliocene. Changes in that distribution are more likely to reflect a response in the amplitude of the underlying seasonal cycle ~~that~~ than ENSO properties (Thirumalai et al., 2013). Nonetheless, the technique should be sufficient to detect presence or absence of ENSO. None of the climate models in PlioMIP ensemble (or elsewhere for that matter) show a lack of interannual variability in the Eastern Equatorial Pacific – in agreement with the results of Scroxton et al. (2011). However, it is doubtful that one would expect a lack of variability in this region, even with a substantially reduced zonal SST gradient in the Equatorial Pacific (Manucharyan and Fedorov, 2014).

The only other observational study of Pliocene climate variability looks at two fossil corals from the Philippines (Watanabe et al., 2012). The δ^{18}O is sampled at regular intervals during the corals' roughly thirty year life span. A periodicity of approximately three years is found the Pliocene corals, which lived between 3.5–3.8 million years ago. This again provides evidence of ENSO variability in the Tropical Pacific. Unfortunately due to natural, internal shifts in ENSO properties on multidecadal timescales (Wittenberg, 2009), it would be impossible to infer an increase in this period with any confidence from the 30 year records available.

4.2 Global dominance

ENSO is the focus of substantial interest amongst the palaeoclimate community, partly because it is the globally dominant mode of climate variability (Deser et al., 2010). It is projected to stay this way for the coming century (Christensen et al., 2013). In the PlioMIP ensemble, ENSO becomes weaker whilst other modes of climate variability do not appear to do so. Is it possible that ENSO becomes so weak that its teleconnected response is not large enough to overwhelm local climate variability? Such a situation was suggested by Brierley (2013) as existing around four million ~~year~~ years ago at the time of the weakest zonal SST gradients in the Tropical Pacific (Fedorov et al., 2013).

Quantitatively detecting a change in global dominance is problematic. However, visual inspection of the leading global empirical orthogonal function can potentially show this. The two leading preindustrial EOFs of NorESM-L show strong signatures in both the North Pacific and the Niño region (Fig. 6a,b). In fact, their principal component timeseries show a marginally higher correlation to the PDO than ENSO – a feature not seen in observations. NorESM-L shows the strongest reduction in ENSO amplitude in the Pliocene across the ensemble (Table 2). For this model, the two leading global EOFs in the Pliocene show no signature in the Tropical Pacific (Fig. 6c,d). A similar feature is not seen with the other PlioMIP models (not shown).

Whilst this analysis does not state that ENSO in the Pliocene was confined to the Tropical Pacific, it at least shows the potential for that to be the case. A lack of ENSO-style periodicities in regions remote from the tropical Pacific in the Pliocene may not denote a change in teleconnection patterns, but rather be indicative of a weaker amplitude for ENSO. Attempts have been made to use present-day ENSO teleconnections to identify mean climate changes during the Pliocene (Molnar and Cane, 2007, 2002) , although they have been dismissed as unconvincing (Bonham et al., 2009) . That debate would further motivate an analysis of ENSO teleconnections in the PlioMIP ensemble. Unfortunately, sufficient temperature and precipitation data does not presently exist in the PlioMIP database to permit such an analysis across the ensemble.

4.3 (Statistical) Signicance

The PlioMIP ensemble shows a weakening and lengthening of ENSO ? There have been many suggestions as to what controls the properties of ENSO. It is beyond the scope of this article to test them all or to investigate the ENSO changes from a process-based approach. However , several possibilities can be easily evaluated from the data analysed here. in the vast majority of the constituent models, but how significant is that? A thorough analysis of the statistical significance of even an individual model's ENSO is a challenge. I will obviously concentrate this discussion on ENSO, but the challenges are even larger for a lower frequency oscillation such as the PDO. Ideally, one would compare the Pliocene ENSO time series to multiple segments of a similar length from the preindustrial control simulations. As the Pliocene time series here are 200 years long, a preindustrial control run of at least ten times that is required to have sufficient segments. The longest preindustrial simulations readily available are only 1000 years (Saint-Lu et al., 2015). This means that there is insufficient data to create a probability distribution to test the possibility of drawing a segment with Pliocene-like ENSO properties. There are methods to estimate the probability without a very long control simulation (e. g. Stevenson et al., 2010). However the interesting factor here is not whether each constituent model's change may or may not be significant. Rather the surprising observation is the consistency across the ensemble in the reduction in amplitude and frequency.

Other model ensembles show a range of behaviours and often contain more members than analysed here. Perhaps So perhaps it is purely coincidence coincidental that the PlioMIP ensemble presents such a coherent message? Using the subset of Estimating the probability of a generic model ensemble showing a given level of coherence is problematic. A very simple approach is to consider each individual model having an equal chance of increase, reduction or no-change in an ENSO property (say its amplitude). For 8 out of 9 ensemble members showing a similar change while the lone dissenter does not show an opposite response (as was found for both amplitude and period here) is therefore:

$$p(\text{8 of 9}) = \frac{2}{3} \times \frac{1}{3^8} = 0.000102 \quad (2)$$

The assumption of the three possible ENSO changes (increase, decrease, no-change) for each model having an equal occurrence may be incorrect. An alternate approach is use the future projections of the CMIP5 models ~~by Taschetto et al. (2014) this probability can be estimated~~and their ENSO changes to estimate this occurrence. The PlioMIP and CMIP5 models are categorised into three groups depending on their Niño 3.4 standard deviation change: decrease, increase or no change. Here ~~"~~'no-change~~"~~' is arbitrarily defined as having an absolute standard deviation of less than 0.05 °C, although the conclusion is robust to other threshold settings. The PlioMIP ensemble therefore forms a set of 9 models with 7 decreasing and 2 with no-change. The CMIP5 ensemble contains 27 models with 8 decreasing and no change in 11 (Taschetto et al., 2014). There 5071 combinations showing a reduction at least as robust as the PlioMIP ensemble out of a total 4.6×10^6. This probability of only 0.01 % is likely somewhat of an underestimate, because the lengths of simulation analysed by Taschetto et al. (2014) are substantially shorter than here (Stevenson et al., 2012). However, it does result in a similar estimate as above.

~~Nonetheless, I consider~~ These calculations suggest that the PlioMIP signal did not occur by chance and is a real feature that needs exploring. Yet one must remember that many ensembles have been created and multiple ENSO properties have been investigated, which somewhat increases the likelihood of results like those seen in this particular ensemble occurring. One would be much more confident that the ENSO response described in sect. 3.1 is a real future of the Pliocene climate, if an underlying mechanism can be found to explain them.

4.4 Physical Mechanisms

There have been many suggestions as to what controls the properties of ENSO. It is beyond the scope of this article to test them all or to investigate the ENSO changes from a process-based approach. However, several possibilities can be easily evaluated from the data analysed here.

The commonality of PlioMIP experiments is in their application of (nearly) identical forcing and boundary conditions changes (Haywood et al., 2011). The ENSO weakening and lengthening should therefore be a response to one of these boundary changes. Bonham (2011) investigated the response of ENSO in HadCM3. She found that changes in topography were the leading order determinant of the ENSO amplitude through a factor separation exercise (after Lunt et al., 2012) . Confusingly, Bonham (2011) finds that topography leads to an increase in ENSO amplitude - potentially the use of a previous iteration of the PRISM topography is the explanation for this different signal. Feng and Poulsen (2014) find a response of ENSO to alterations in the elevation of the Andes mountain range, using CCSM4 simulations. The PRISM reconstruction has lower Andes elevation in the Pliocene (Haywood et al., 2011). Unfortunately, Feng and Poulsen (2014) show that a lower Andes would result in a shorter ENSO period – something that even the CCSM4 PlioMIP simulation does not show (Table 2). Therefore, any Andean response must be masked by another factor (assuming it is not model dependent, which is as yet untested).

Much of the interest in Pliocene ENSO has been driven by the reduced zonal SST gradients ~~seen in~~ suggested for the mean climate state (Wara et al., 2005; Fedorov et al., 2013). It has been anticipated that ENSO properties are related to this gradient (e.g. Fedorov and Philander, 2001; Zhang et al., 2012b), although the precise nature of this relationship appears complicated (Manucharyan and Fedorov, 2014). Figure 7 shows the Equatorial SST in the Pacific (averaged between 5° S–5° N). It is clear that all ensemble members simulate an West–East gradient, although with a range of fidelity to the ~~observed gradient~~range of reconstructed gradients. The warmth of the Pliocene can be seen by the fact that all models show at least 0.5 °C of warming at all longitudes. However there is no consistent preferential warming seen in the Eastern Equatorial Pacific, as seen in the palaeobservations (Dowsett et al., 2012; Fedorov et al., 2013). Therefore a consistent reduction in the zonal SST gradient cannot explain the robustly weaker and longer ENSO. A similar lack of explanation is borne out, when assessing whether the mean state becomes more El Niño like (Fig. 8; Collins and The CMIP Modelling Groups, 2005).

An alternate possibility that can be easily tested is the suggestion that the amplitude of ENSO is inversely correlated to the seasonal amplitude (Liu, 2002). This possibility has already been questioned by Braconnot et al. (2011) and the PlioMIP ensemble does not show support for it either. Whilst there are changes in the seasonal cycle of Niño 3, they are not coherent across the PlioMIP ensemble (Fig. 9).

5 Conclusions

The Pliocene Model Intercomparison Project (PlioMIP) has coordinated nine coupled climate models to simulate the conditions of the mid-Piacenzian. Through analysis of sea surface temperature, I have described the interannual climate variability seen across the ensemble. Although some models show changes in the Indian Ocean Dipole or Pacific Decadal Oscillation, there was little coherency throughout the ensemble in these changes. Four different properties of the El Niño Southern Oscillation have been isolated and the Pliocene changes in them investigated. There is no coherent change in the prevalence between the cold tongue and warm pool types of El Niño – in keeping with future projections (Taschetto et al., 2014). Analysis of the structure of ENSO finds ~~an~~ a slight expansion of the phenomenon further polewards – unlike the pattern found by Power et al. (2013) for the future projections.

The finding that eight of the nine PlioMIP models show a reduction in Niño 3.4 ~~variance~~ amplitude and a shift towards lower frequencies was unexpected. The chance of such a coherent message arising by chance is slim, when considering the range of results in the CMIP5 future scenarion runs (Taschetto et al., 2014). Three possible suggestions were investigated in the hope of explaining this result: namely reductions in the annual mean zonal temperature gradient (Fedorov and Philander, 2001; Zhang et al., 2012b), Andean uplift (Feng and Poulsen, 2014), and seasonal cycle alterations. None was found to have much explanatory power and so the real reason for this resultwill require investigationUntil further investigation posits a viable physical mechanism behind this result, the possibility of it occurring by random chance cannot be satisfactorily dismissed, despite calculations suggesting it to be highly unlikely. Recent developments in process-based analysis (e.g. Jin et al., 2006) that are currently being applied to modern simulations (Bellenger et al., 2013) may help find the answer to this conundrum.

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Table 1. Simulations contributing to the PlioMIP ensemble (see Sect. 2.1 and Haywood et al., 2013, for details). The resolution given relates to the deep Tropics for models with a varying ocean resolution. The length analysed represents the number of model years uploaded to the PlioMIP database – the simulation is often much longer.

	Institution	Resolution				
Model	Initials	Atmos.	Ocean	Length Analysed ~~Record Length~~ *	CMIP5	Reference
CCSM4	NCAR	0.9 × 1.25°	0.4 × 1°	200, 100	Yes	Rosenbloom et al. (2013)
COSMOS	AWI	T31	3 × 1.8°	100, 150	No	Stepanek and Lohmann (2012
FGOALS-g2	LASG	2.8 × 2.8°	0.5 × 1°	100, 100	Yes	Zheng et al. (2013)
GISS-E2-R	NASA/GISS	2 × 2.5°	1 × 1.25°	200, 200	Yes	Chandler et al. (2013)
HadCM3	UKMO	2.5 × 3.75°	1.25 × 1.25°	198, 200	Yes	Bragg et al. (2012)
IPSLCM5A	LSCE	3.75 × 1.9°	0.5 × 2°	200, 200	Yes	Contoux et al. (2012)
MIROC4m	JAMSTEC	T42	0.5 × 1.4°	200, 100	No	Chan et al. (2011)
MRI-CGCM2.3	MRI	T42	0.5–2.5°	200, 200	No	Kamae and Ueda (2012)
NorESM-L	BCCR	T31	1.5 × 3°	200, 200	No	Zhang et al. (2012a)

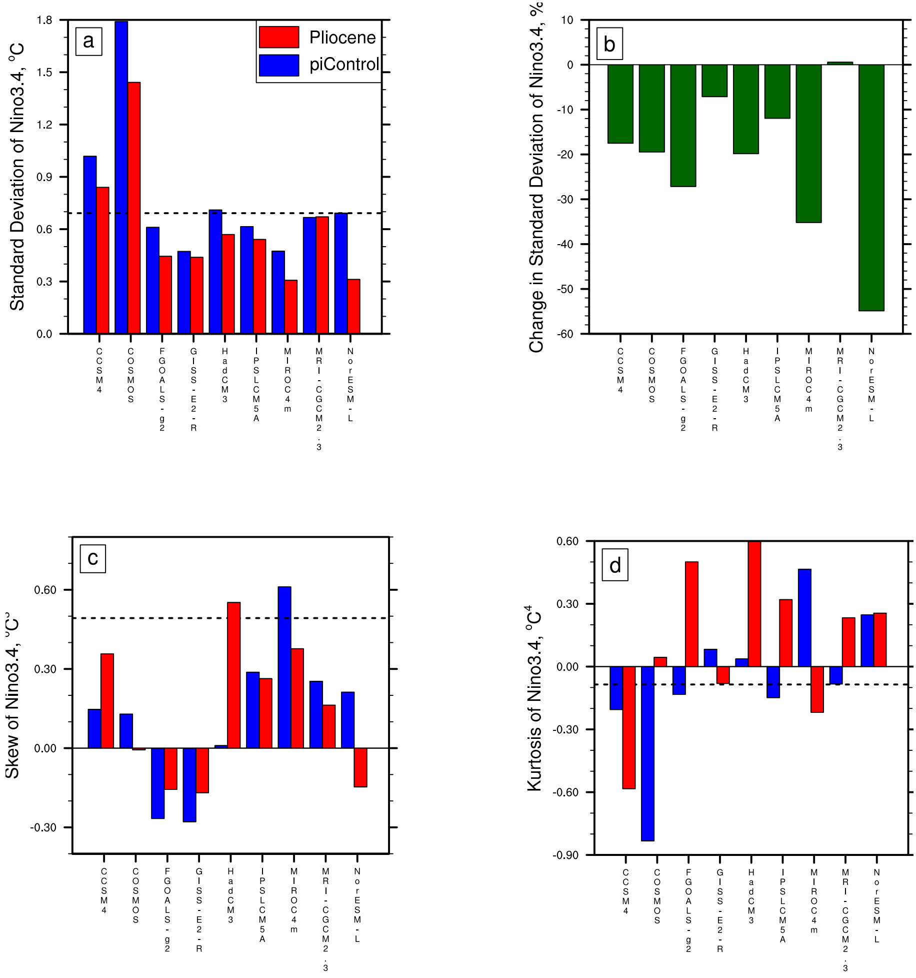
* Preindustrial followed by Pliocene simulation.

Table 2. Properties of area averaged sea surface temperature indices (see Sect. 2.2 for details). The period listed below is that with the greatest spectral power. The preindustrial and Pliocene simulations, along with the difference between them, are denoted by piCtl, Plio and Diff, respectively.

	Niño 3.4 std dev. (°C)			Niño 3.4 period (years)			DMI std dev. (	
Model	piCtl	Plio	Diff	piCtl	Plio	Diff	piCtl	Plio
CCSM4	~~1.04~~1.02	~~0.71~~0.84	−~~0.33~~0.18	4.1	6.9	2.8	~~0.20~~0.46	~~0.23~~0.48
COSMOS	~~3.20~~1.79	~~2.08~~1.44	−~~1.16~~0.35	6.5	4.2	−2.3	~~0.11~~0.34	~~0.13~~0.36
FGOALS-g2	~~0.37~~0.61	~~0.20~~0.44	−~~0.18~~0.17	6.5	7.4	1.0	~~0.06~~0.25	~~0.02~~0.17
GISS-E2-R	~~0.22~~0.47	~~0.19~~0.43	−0.03	3.4	4.3	0.8	~~0.05~~0.22	~~0.05~~0.22
HadCM3	~~0.50~~0.71	~~0.32~~0.57	−~~0.18~~0.14	3.8	4.2	0.3	~~0.11~~0.32	~~0.14~~0.37
IPSLCM5A	~~0.38~~0.61	~~0.29~~0.54	−~~0.08~~0.07	3.3	5.1	1.8	~~0.13~~0.37	~~0.08~~0.29
MIROC4m	~~0.22~~0.47	~~0.09~~0.31	−~~0.13~~0.17	5.9	7.7	1.8	~~0.21~~0.45	~~0.16~~0.41
MRI-CGCM2.3	~~0.44~~0.67	~~0.45~~0.67	~~0.01~~0.00	2.2	2.5	0.2	~~0.03~~0.18	~~0.03~~0.19
NorESM-L	~~0.48~~0.69	~~0.10~~0.31	−0.38	4	4.1	0.1	~~0.17~~0.41	~~0.06~~0.24
Ensemble Mean	~~0.76~~0.78	~~0.49~~0.62	−0.27	4.4	5.1	0.7	~~0.12~~0.33	~~0.11~~0.30
ERSST Obs.	~~0.48~~0.69	–	–	5.5	–	–	~~0.06~~0.25	–

Table 3. Properties of Empirical Orthogonal Functions (EOFs) of the Indian Ocean. The percentage of variance explained (Var. Expl.) by each model's first two EOFs and the period with the most spectral power is shown. The correspondence of each EOF to physically meaningful modes of variability has been determined by visual inspection. The preindustrial and Pliocene simulations are denoted by piCtl and Plio, respectively.

		Mode		Var. Expl. (%)		Period (years)	
Model	EOF	piCtl	Plio	piCtl	Plio	piCtl	Plio
CCSM4	1st	Basin	Dipole	24.4	29.3	4.1	6.9
	2nd	Dipole	Basin	22.3	20.4	4.0	6.9
COSMOS	1st	Basin	Basin	47.3	37.7	7.1	4.1
	2nd	Dipole	Dipole	11.1	14.5	2.8	4.9
FGOALS-g2	1st	Basin	Basin	33.4	29.2	6.9	3.1
	2nd	Dipole	Dipole	12.8	10.4	6.5	4.0
GISS-E2-R	1st	Basin	Basin	27.2	24.6	3.9	2.9
	2nd	Dipole	Dipole	11.0	11.9	3.3	6.7
HadCM3	1st	Dipole	Dipole	18.6	18.1	5.0	4.2
	2nd	Dipole	Dipole	11.4	14.1	5.3	7.7
IPSLCM5A	1st	Basin	Basin	22.9	20.0	3.3	5.1
	2nd	Dipole	Dipole	11.9	13.2	6.5	7.7
MIROC4m	1st	Basin	Dipole	28.9	25.7	5.1	6.3
	2nd	Dipole	Dipole	16.0	13.7	3.9	2.9
MRI-CGCM2.3	1st	Basin	Basin	37.7	35.1	4.1	4.8
	2nd	Dipole	Dipole	8.8	8.9	7.4	5.0
NorESM-L	1st	Basin	Basin	21.0	20.2	4.0	4.5
	2nd	Dipole	Basin	14.3	12.7	5.1	2.0
ERSST Obs.	1st	Basin	–	39.1	–	3.6	–
	2nd	Dipole	–	11.8	–	5.6	–



a
Pliocene
piControl
Standard Deviation of Nino3.4, °C
b
Change in Standard Deviation of Nino3.4, %
c
Skew of Nino3.4, °C³
d
Kurtosis of Nino3.4, °C⁴
CCSM4
COSMOS
FGOALS-g2
GISS-E2-R
HadCM3
IPSLCM5A
MIROC4m
MRI-CGCM2.3
NorESM-L

Figure 1. The moments of the distributions of the Niño 3.4 sea surface temperature anomalies in the ensemble members. The first moment (i.e. the mean) is zero by definition. The ~~variance~~ standard deviation shows the amplitude of the SST variations. If the skew is positive, then the El Niño tail is stronger than the corresponding La Niña state. If the kurtosis is greater than 0, then the distribution is more peaked than a Gaussian. The dashed line shows the moment of the ERSST observations.

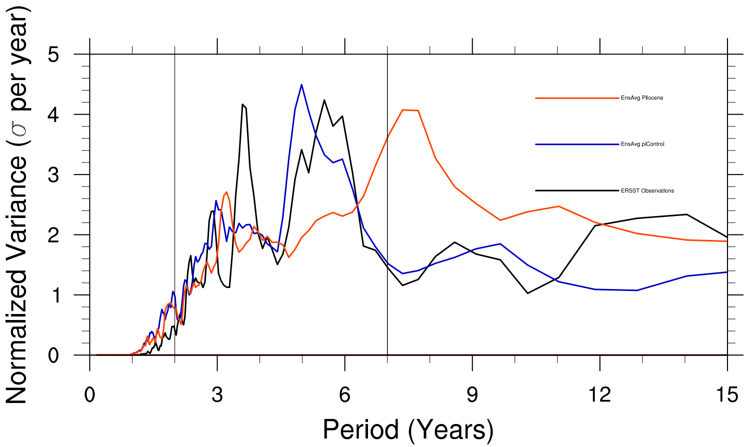


Figure 2. The ensemble average power spectra of the Niño 3.4 sea surface temperature anomalies.

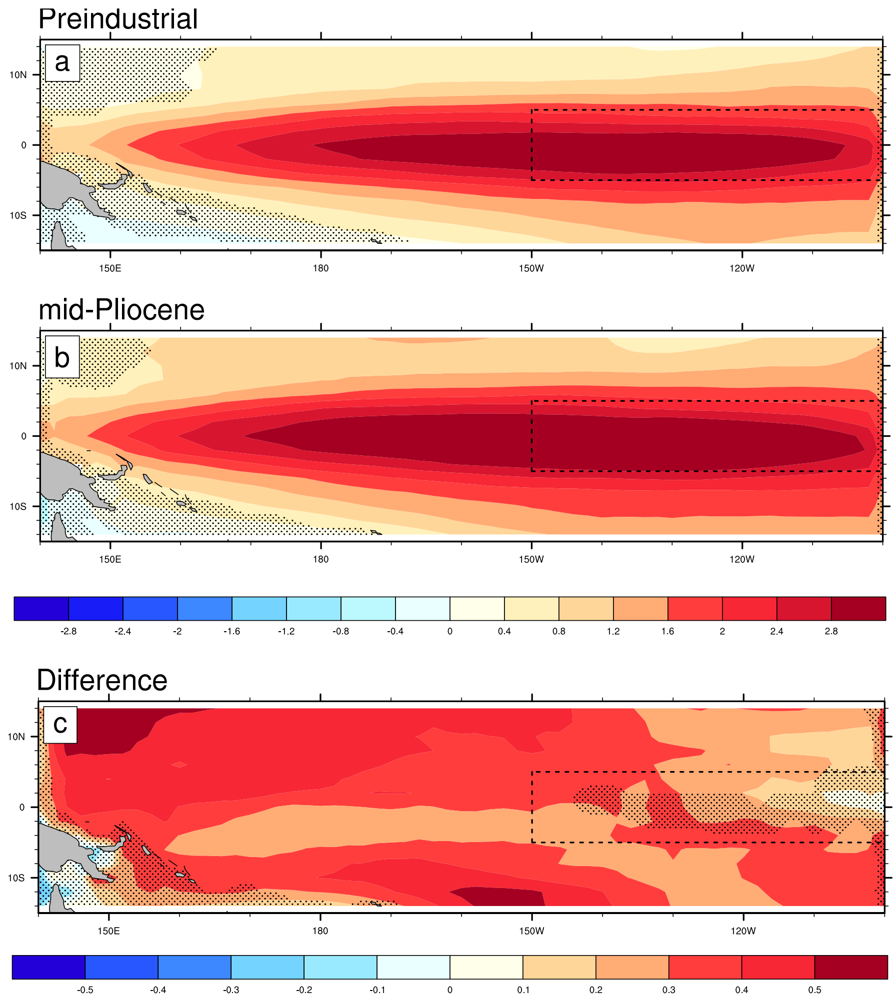

Preindustrial
a
10N
0
10S
150E
180
150W
120W
mid-Pliocene
b
-2.8
-2.4
-2
-1.6
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
1.6
2
2.4
2.8
Difference
c
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5

Figure 3. The ensemble average empirical orthogonal functions computed for the tropical Pacific. All patterns are defined to be positive in the Niño 3.4 region (dotted line). Stippling indicates that less than eight of the nine models agree on the sign of the change. The change in standard deviation is defined as Pliocene – preindustrial

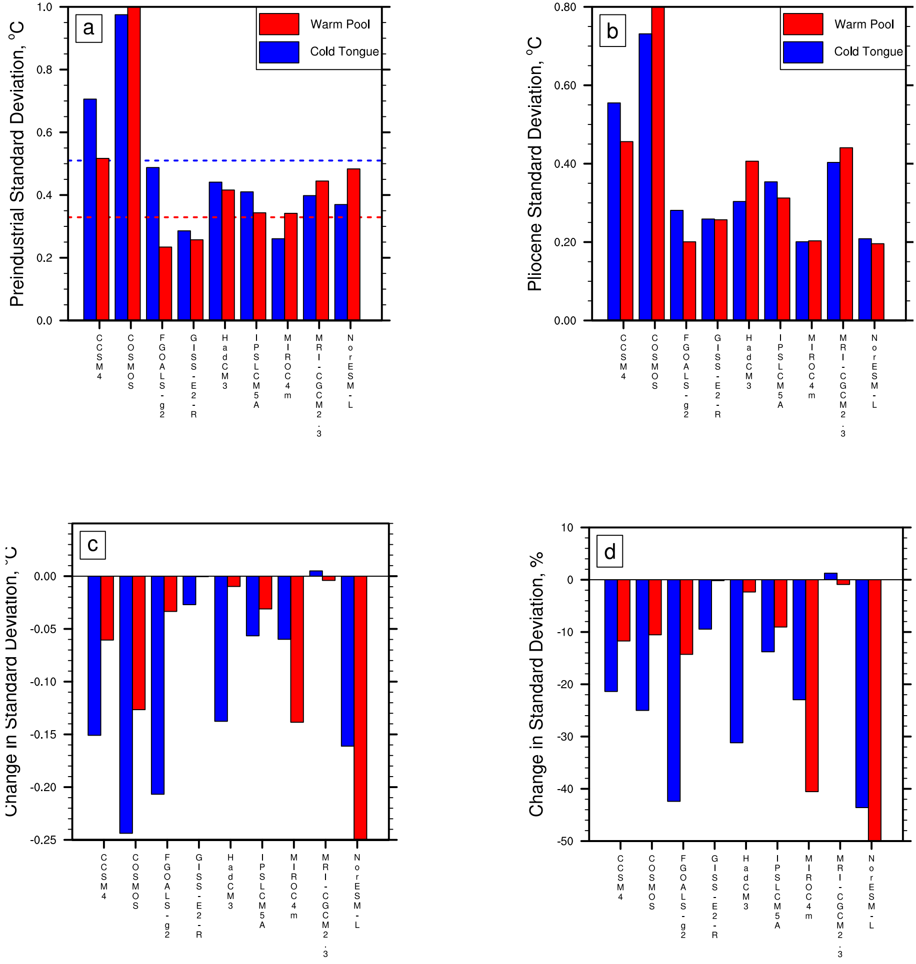
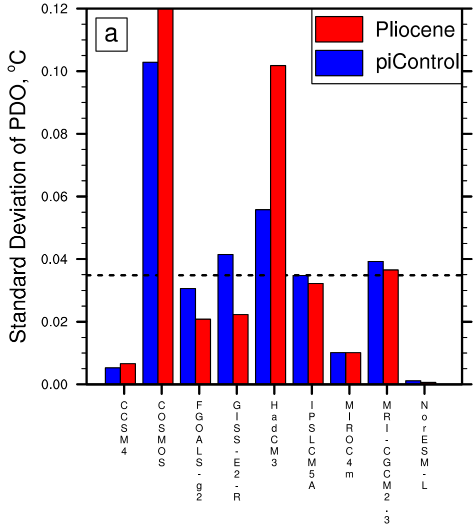

a
b
c
d
Warm Pool
Cold Tongue
Preindustrial Standard Deviation, °C
Pliocene Standard Deviation, °C
Change in Standard Deviation, °C
Change in Standard Deviation, %
CCSM4
COSMOS
FGOALS-g2
GISS-E2-R
HadCM3
IPSLCM5A
MIROC4m
MRI-CGCM2.3
NorESM-L

Figure 4. Response of the two different flavours of ENSO considered separately. The flavours are disaggregated using the method of Ren and Jin (2011) into cold-tongue and warm-pool types. The red and blue dashed lines indicated the ~~variance~~ standard deviation found in the ERSST observations.


a
Pliocene
piControl
Standard Deviation of PDO, °C
0.12
0.10
0.08
0.06
0.04
0.02
0.00
CCSM4
COSMOS
FGOALS-g2
GISS-E2-R
HadCM3
IPSLCM5A
MIROC4m
MRI-CGCM2.3
NorESM-L

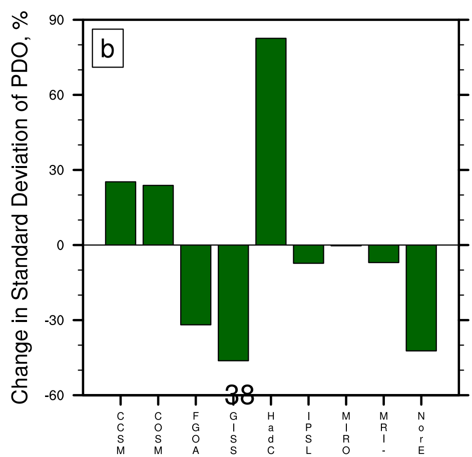

b
Change in Standard Deviation of PDO, %
90
60
30
0
-30
-60
CCSM
COSM
FGOA
GISS
HadC
IPSL
MIRO
MRI-
NorE

Figure 5. The standard deviations of Pacific Decadal Oscillation – defined as the first EOF of the North Pacific. The dashed line shows the standard deviation of the PDO in the ERSST observations.

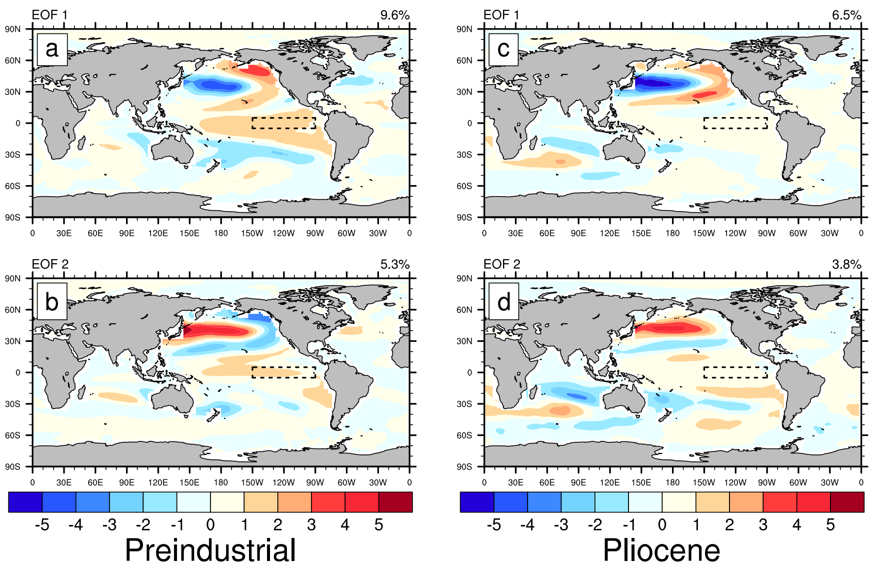


Figure 6. The first two EOFs of the global SST anomalies in NorESM-L for both the preindustrial simulation (left) and the Pliocene simulation (right). The percentage of the variance that each EOF explains also shown.

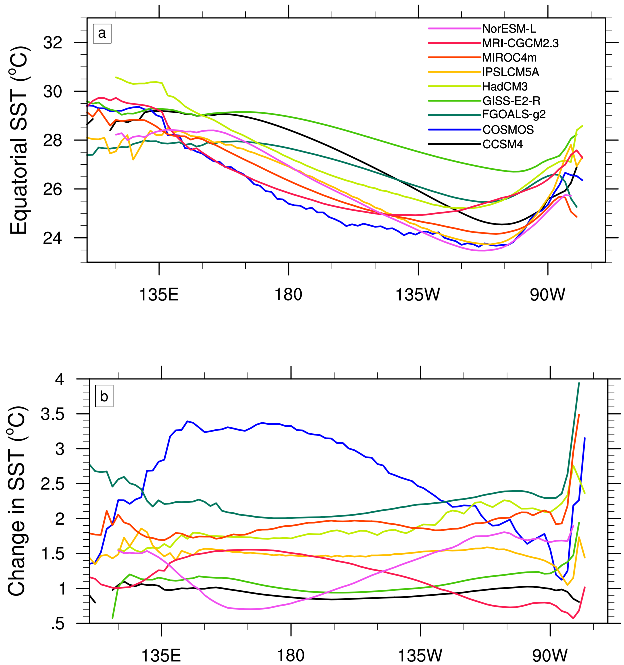


Figure 7. The annual mean Pacific temperature gradients along the Equator in the preindustrial simulations and the change in the Pliocene simulations.

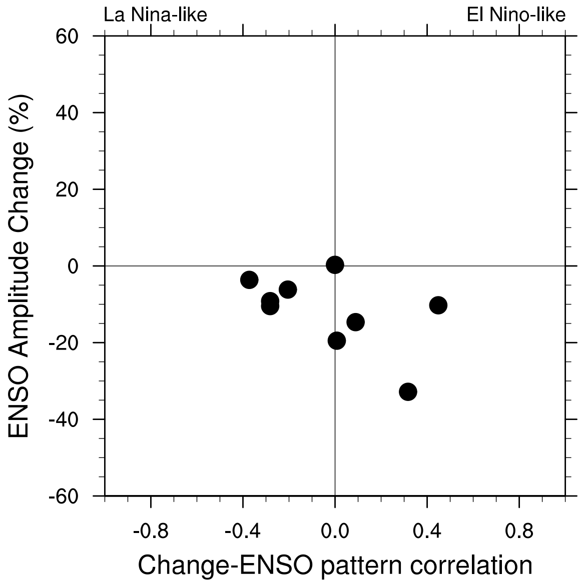


Figure 8. A scatterplot of the change in ENSO amplitude (from Fig. 1) to the correlation of Pliocene mean state changes projected onto the model's leading tropical Pacific EOF.

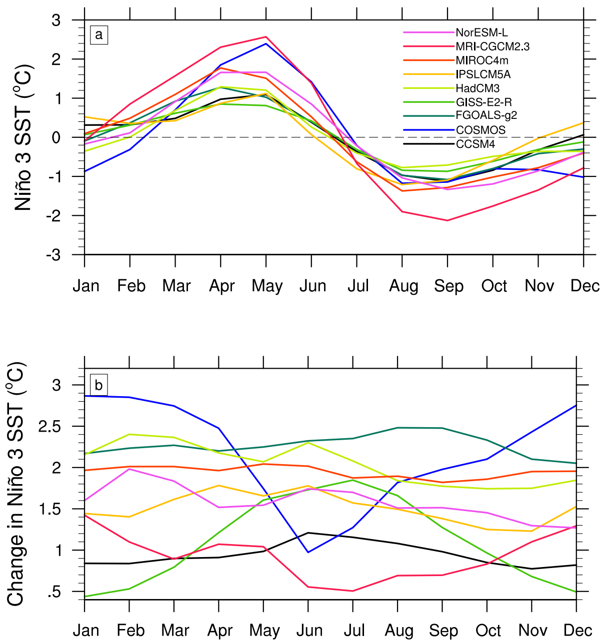


Figure 9. The seasonal cycle of the Niño 3 ~~SSTs~~ region average SST and its changes in the nine models.