Response to Reviewers

Reviewer 1
Main points

A first point concerns the considered ensemble of simulations: I wander why MPI-ESMP, for instance, is not included in the list (a millennial control run is also available in the CNIP reportistory for this model). Also, there are at least two full-forcing past1000 simulations with GISS-E2-R available, which one is used here? And why not use both?

- The MPI-ESM-P model was processed but excluded from the multi-model ensemble by error, which has now been corrected. In addition we now explain which GISS-E2-R realization was used and why we selected only one ("For GISS-E-2-R, we include only one contributing realisation (r1i1p121) to constitute a multi-model ensemble of one ensemble member from each model.")

A focus on statistical significance is of course important to substantiate all the results in section 4.1 and 4.2, and especially those concerning differences in ENSO statistics/ metrics through the last millennium as these are part of the main conclusions of the study. The methods are well described in section 2.3, but I failed to see the significances for instance for figures 7 and 8.

- Figure 7 has now been removed on recommendation of Reviewer 2. The significance of correlations in Figure 8 is now included.

Also, I wander why the authors decided to use the 20CR when only the 1976-2005 period of historical simulations is considered (Table 1). Why not use the whole period covered by the 20CR, or use instead more or different available reanalysis products? As the authors also report in the introduction, the instrumental record provides limited guidance for understanding the range of ENSO behaviors. Still, observations indicate that ENSO properties have changed over the last several decades, in particular with increased frequency of so-called Central Pacific events in most recent decades - the ones considered in this assessment (see, for instance: Pascolini-Campbell et al., 2014). It has been emphasized that different "types" of El Niño exist during the observational period that have substantially different characteristics (including different teleconnections, as shown for instance by Graf and Zanchettin, 2012). This observed behavior should be considered when discussing the simulations-reanalyses comparison over such a short and peculiar period of time.

- We selected a short period of time for comparison of the historical experiment and the 20CR reanalysis data so that we could focus on ENSO characteristics, rather than the anthropogenic signal evident over the extended period. We have now made clear there is greater variability in ENSO over the extended period, and that the recent period is unusual, and hence that we are only evaluating part of the ENSO system in comparing datasets over a short period ("Models were compared to twentieth century reanalysis data (20CR) (Compo and Whitaker, 2011) as a widely proxy on observed climate (King et al., 2014; Klingaman and Woolnough, 2013). We compare datasets for the period of 1976-2005, rather than an extended period, due to greenhouse forced non-stationarities over the post-industrial era. It should be noted that ENSO properties have changed over the last several decades, in particular with increased frequency of Central Pacific centred events in recent decades, which have substantially different characteristics (Pascolini-Campbell et al., 2014). Hence model skill in recent decades does not ensure that all variations of ENSO are equally well captured.")

A similar question concerns the limited temporal domain used for the Mid-Holocene simulations: is 100-year a long enough period to guarantee robust estimates about ENSO behavior, given the variability that is reported about the last millennium? The authors should consider expanding the "model evaluation" section and related discussion: in fact, they mention six metrics used to evaluate ENSO, but in the following text there is very limited discussion on this.

- The model evaluation section has now been clarified to make clear that we are referring to the Bellenger et al study on model evaluation of ENSO. The 100 year period for the mid Holocene is used to provide an estimate of the mean climate state and represents the minimum period provided by all models. We do not suggest that 100-year period provides an exhaustive representation of possible ENSO behavior, but rather that it useful for examining possible boundary condition influences.

A deeper analysis could substantiate interpretation of some results which appears at occasions to be not conclusive. For instance, concerning the difference between historical and last millennium simulations in Figure 1 (section 4.2), the authors provide an only vague interpretation (1592/21-25), while I felt it was exactly the aim of this study to provide an answer to this regard. I also did not find conclusive the analysis of internal versus externally forced ENSO variability in section 4.1. The authors themselves agree that this is the case (1598/26-29), so I wander what the aim of this section is: overall, I suggest the authors to either deepen the analysis or largely restructure/reduce this section. Some specific concerns/suggestions I have on this are: when external forcing is considered, such as variable solar irradiance, why not substantiating the results with a wavelet coherence analysis (1590/15-24)? Also, the assessment of the role of volcanic forcing is too vague: no result is shown (e.g., from a superposed epoch analysis as typically done in these cases), only three major eruptions are reported in Figure 3 (but not the 1815 Tambora, why?), and only one eruption is discussed in the text. Later on, volcanic forcing (1591/23) as well as combined volcanic and solar forcing (1591/27) are reported again as a possible important factor for ENSO evolution. The summarizing paragraph (1591/21-1592/2) appears again to be too vague ("may be... may reveal...").

- We have now shortened this section as recommended and we also provide a more specific discussion of volcanic forcings is now provided in section 6, with greater reference to previous model-based studies.

Minor points

1581/7: typo ("is a is a")

- This has been corrected.

1581/8: maybe Zou et al. (2014) is a worthy addition here

- The Zou et al (2014) study is primarily focused on pre-industrial CMIP5 simulations, not future projections, so is not added here.

1581/17: I guess it is "does NOT capture"

- This has been corrected.

1585/14: remove "in"

- This has been removed.

1585/18: isn't it Fig. 1 (and not Fig. S1)?

- Fig. 1 shows composited anomalies and Fig S1 the EOF analysis.

1587/13: please check that acronym SD is defined

- This has been corrected.

1587/21: is MIROC5 the same as MIROC-ESM?

- This has been corrected to MIROC-ESM

1588/5: I am not sure what “physically plausible” means in this instance, maybe expand a bit?

- This description was vague and has now been deleted during the shortening of this section.

1590/15-21: Can you be more specific here about the role of solar activity? Are the prevailing La Nina like conditions induced by increased solar activity a result of this study or from previous ones? Actually Figure 3 does not seem to show this as the 1258 seems rather associated to cold anomalies.

- This discussion on solar activity has now been deleted as it was not contributing to the discussion of teleconnection stability.

1591/27: combination of

- This has been corrected

1592/17: resemble

- This has been corrected

1593/4-5: I wander whether the linear relationship is really different for the two experiments, or, rather, the regression is for both not significant (and then differences do not really matter).
1593/6-7: I was not able to see where significance is reported? I think it is important to report it since by eye I wouldn’t say that for some regions/variables the changes are so dramatic…
1593/15: same as above: where is significance reported?

- The statistical significance of correlations is now shown in Figure 7 and 8, and in the discussion.

1594/5: sites in the tropical …

- This has been corrected

1596/23: we find that ENSO…

- This has been added.

1597/3-5: I think the use of parentheses here is confusing

- This has been expanded and written out explicitly (‘Models suggest it may be inherently difficult to deconvolve variability in the NINO3.4 region and local-scale, teleconnected climatic change in the West and East Pacific regions. The West Pacific Warm Pool is likely sensitive to subtle shifts in the western extent of the warm tongue characterising positive (El Niño) episodes, and conversely to the cool anomalies charactering La Niño episodes.’

1597/25: “the stability ...is ...variable” sounds strange, so maybe rephrase?

- We have removed “stability” .

1598/6: why necessarily?

- Necessarily has been removed

1598/8: volcanic)

- It is unclear what should be changed here.

Fig. 1 caption: check space in “La Niña”

- This plot has been replaced by a multi-panel plot showing each model.

Fig. 2: there is a strong peak at 6-year period in the historical IPSL-CM5A-LR simulation, any thoughts on this?

- This peak was likely an artifact of processing the short historical period (1976-2005). When models are processed over 1906-2005, most reveal a strong peak around this period, which is now discussed in section 4.1.

Fig. 3: the anomalies for bcc-csm1-1 are noticeably mostly negative, so I wander how anomalies are exactly calculated (not from full-period average?)

- This was an artifact of processing error and has now been corrected. We thank the Reviewer for identifying this, which has been corrected and now included in Supplementary Figure 4.

Fig. 4 caption: check panel for 20CR precip

- It is unclear what should be corrected here.

Fig. 5: maybe it could be useful to add a Box-Whisker plot for the past1000 simulations, to see how they compare with the piControl.

- We do not directly compare the piControl simulation to the Last Millennium because they have a different number of contributing models.

Fig. 8: To me it seems that the only changes in the West Pacific for temperature are associated to volcanic eruptions (1258, Kuwae). Does this support the hypothesis of a volcanic influence? The question is also how much short-term effects could affect the long-term (100 year in this case) statistics. Was any smoothing applied to the series? How would the statistics change if the data around the years of major eruptions are removed from the analysis?

- We now discuss details of the timing of volcanic eruptions and changes in the remote-local relationships in section 6, including the persistence of such influences. We did not apply smoothing to this aspect of the analysis.

Supp. Fig. 2: should one of the “showing” be removed?

- This figure has now been deleted.

Supp. Fig. 6: what does the blue shading indicate in panel a?

- This figure has now been deleted.

Reviewer 2
Main points

This study utilises the ensemble mean of 6 CMIP5 models that have the required set of experiments. The authors argue that, while they acknowledge each model is not free of biases, model bias is not a prohibitive issue for investigating the temporal stability of teleconnections [p. 1588 (25)]. I tend to agree with this argument, but it is still important to provide an indication to what extent the multi-model mean (MMM) represents the entire 6 samples. This is particularly necessary as model selection have not been extensively conducted, perhaps given the limited models available. Even one or two models could exhibit severe bias that may skew the MMM, especially in the climatology that can affect teleconnection patterns. A severe cold tongue bias for instance can spuriously shift rainfall teleconnection. In this case, rainfall in the western Pacific or

Maritime Continent and the Nino3.4 could be positively correlated, while in reality or in more realistic models they should be negatively correlated. Averaging these teleconnections across models would result in a weak correlation as seems to be the case in Fig. 8. It would be a better approach to present the results for each model or present a confidence interval over each of the ensemble mean. For example, in Fig. 8 a confidence interval (or even better each model correlation value) should be added over the MMM.

- We have now included details of each model, as recommended. Furthermore, we now show each model correlation and statistical significance in Figures 7 and 8.

Li et al. 2013 (see their Fig. 2) found that their paleo proxies in the west Pacific (Maritime Continent) and east Pacific generally correlate quite well with Nino3.4, in contrast to those suggested by Fig. 8. It is necessary to comment in Section 4.2 the possible reasons for this mismatch (e.g., due to certain model biases, as per above points). Also, it would be good to put the results of Section 4.2 in the context of other existing studies.

- We have now discussed this key difference with Li et al 2013 and discussed our results in a broader context in section 6.

In light of the above comment, it is actually necessary for the readers to get a better sense in how each of the 6 models performs in terms of the ENSO characteristics and in terms of the mean climate. In section 3 (page 1587) it seems that the authors tried to do this: "Here, ENSO was examined through 6 metrics...." but there are no figures that show some of these metrics (e.g., seasonality, Nino3 vs Nino4 amplitude, etc). There are by now a number of studies evaluating the fidelity of ENSO simulation. In terms of climatological bias, at present the authors are comparing the multi-modelmean vs observations in Fig. 4 where climatological bias is severe. Perhaps one or two models are significantly contributing to the westward bias (e.g., IPSL-CM5A-LR, HadCM3, possibly the GISS-E2-R as well; see Taschetto et al. 2014 J. Climate, their Fig. 3c). IPSL-CM5A-LR for instance cannot simulate the nonlinear response of rainfall to Nino3 SST anomalies that underpin extreme El Nino (Cai et al. 2014 Nature Climate Change).

- The model evaluation section has been altered to clarify this point. First, it is now made clear that the discussion of ENSO metrics refers to the Bellenger et al study. Next, we now include plots of each model in multi panel figures (Figures 1-4, 7 and 8). Finally, we also discuss biases in section 6 in further detail, with reference to Cai et al 2014. ("This study highlights several avenues for further research. … Several models have known difficulties simulating aspects of ENSO, such as the nonlinear response of rainfall to extreme El Niño episodes (e.g., Cai et al., 2014). Additional targeted experiments within a single climate model would provide further insight into the apparent complexity of ENSO impacts through time.

Shouldn't HadCM2 be HadCM3? HadCM2 is an old model used in IPCC 2nd assessment report, definitely does not contribute to CMIP5.

- In the original manuscript, this model was mistakenly referred to as HadCM2 in the text and HadCM3 in the figures. This has now been corrected throughout to HadCM3.

The authors chose to use Nino3.4 to represent ENSO based on the similarity between the MMM of EOF1 surface temperature in historical and past1000 runs. However, this does not take into account the fact that the temperature pattern changes through time. At certain epochs (of say 30 years), Nino4 can better capture the predominant ENSO characteristics over that particular epoch (E.g., after the 90s – McPhaden et al. 2011

GRL; possibly mid Holocene – Karamperidou et al. 2015, Paleoceanography), and at other epochs, Nino3 could be better. Spatial changes in ENSO pattern are not discussed in this present paper, but it is an important aspect as far as teleconnection is concerned. This should be discussed to a certain extent in the manuscript. Section 4.3 for instance should mention recent results by Karamperidou et al. (2015 Paleoceanography) in which they used CCSM4 model that the mid Holocene involves a change in the spatial pattern of ENSO from eastern Pacific to central Pacific. See also Carre et al. (Science).

- We now include a supplementary figures addressing spatial changes and Nino3 and Nino4 indices. In addition, we now compare the Last Millennium simulation with a 100 year historical period (1906-2005). Furthermore, we explicitly discuss changes in spatial patterns in section 6, including the references recommended.

p. 1584 (5): Is it air temperature or sea surface temperature for the Nino3.4? It is also not clear how composites are calculated here. Is it for the 6 consecutive months or just annual mean?

- This has now been clarified ("El Niño episodes were defined based on simulated surface air temperature anomalies in the NINO3.4 region, with events defined in the models when NINO3.4 temperature anomalies were >0.5 K for at least six consecutive months (Trenberth, 1997). Conversely, La Niña episodes were defined when NINO3.4 temperature anomalies were <-0.5 K for at least six consecutive months. Spatial patterns are examined by compositing monthly temperature and rainfall anomalies into positive (El Niño) and negative (La Niña) phases using these definitions for all CMIP5 models analysed.")

Various studies (e.g.., Li et al. 2013) have used other locations more remote than those used in this present paper for proxy reconstructions. As the authors argue that it is important to link remote proxies with those in central Pacific, why not include far more remote regions as well (e.g., North Pacific, Central Asia) to better illustrate their argument.

- We agree that it would be interesting to next investigate more remote regions. However, the current study specifically focuses on the tropical Pacific and we now identify this as an avenue for future work in section 6 (" In addition, various studies have linked remote proxy variability to the tropical Pacific (e.g., Li et al., 2013) and hence it would useful in the future to investigate regions remote from the Pacific basin, such as in North America or China.")

Fig. 3: It's worth mentioning that the higher power at low frequency in the past 1000 yr runs is also likely attributed to the much longer time series than the historical (30 yrs), better resolving the low-frequency variability.

- This figure has now been modified to included extended historical data from 1906-2005).

P1591 (10), The first sentence implies variability in control simulations is similar to that in past1000, but the subsequent sentences contradict that. It would be easier to compare with Fig. 2 if the power spectra in Fig. 6 are computed using 100-yr samples. It is not clear whether the differences between the two simulations are due to the different length of time series.

- We have now shortened this section and have clarified where information appeared to be contradictory. The range of spectra shown in (revised) Figure 4 and Figure 6 are for 100 –year samples.

p.1592 (20), the difference in the magnitude of the teleconnection patterns in Fig. 1 between past1000 and historical should more likely be due to the averaging of more samples in the past1000 simulations (compared with only 30 years in historical). Actually statistical significance can be added in Fig. 1 by constructing confidence interval based on 30-yr chunks in the past1000 across the 6 models. Do the same for the 30-yr historical. This will then allow determination whether the ensemble means between the historical and past1000 yr are significantly different.

- We now include details of each model and also compare Last Millennium data to the historical period of 1906-2005, rather than the last 30 years of the experiment.

Minor points

The line specs in Fig. 7 are confusing. Why are there 3 different colours for the fitted line? On the left panel the black lines seem to match the blue dots better, so I'm not sure which one is for which. I think Fig. 7 can be culled since the same information can be found in Fig. 8. The historical values can be added in Fig. 8 instead.

- This suggestion has been included, with original Figure 7 culled and historical values included on the same figure as the Last Millennium values.

Again, what does Fig. 8 look like in each model? Insert horizontal lines indicating statistical significant level in Fig. 8.

- The original Figure 8 has now been modified to included details of each model and statistical significance. In the revised manuscript, the precipitation and surface temperature are now shown as separate figures.

This manuscript is well written but it could be shorter as there appears to be a lot of repetitions, e.g.,: p. 1592 (15) first, second, and third sentences basically convey the same message. It need not be stated three times, especially in the same paragraph. A lot of information stated in Section 2 is again repeated in Section 4 (e.g., p. 1593 (10)). P1587 (20, 25): "Models that have.....In addition, ...The MIROC-ESM....(Fig.3)" is a long unnecessary repetition from Section 2 (page 1584). Could consider shortening Section 2 and integrate it to the other sections or move it to an appendix.

- We have made substantial changes to section 2, in order to remove repetition and removing the discussion on various forcings that did not contribute to understanding the stability of teleconnections.

The literature review is lacking on ENSO behaviour response to greenhouse warming, and model-based studies on the sensitivity in the relationship between ENSO and background climate state (p. 1581). A number of recent studies beyond the Collins et al. 2010 (Nature Climate Change) have found that there is indeed inter-model agreement in the response of ENSO to greenhouse warming. Apart from the Power et al. (2013) paper, the other studies show that this response appears to be in the form of an increase in the frequency of extreme El Nino and La Nina (Santoso et al. 2013 Nature; Cai et al. 2014; 2015, Nature Climate Change). It would be good to mention these studies in the introduction to provide a more updated background literature. The model projected change toward more extreme ENSO occurrences under greenhouse warming can provide an interesting avenue for paleo studies to investigate.
1st paragraph on page 1581: "observed changes in the character of ENSO since mid-70s towards a dominance of El Nino" is not accurate, since late 90s the mean state has changed toward a La Nina-like (e.g., England et al. 2014, Nature Climate Change; Hu et al. 2013 J. Climate 26, 2601-2613).

- This review has now been expanded and updated to reflect more recent model-based studies ("While changes in ENSO behaviour may occur under future global warming (Power et al., 2013), there is a large dispersion in global climate model (GCM) projections of changes in ENSO characteristics (e.g. Collins et al., 2010; Vecchi and Wittenberg, 2010), and hence the sensitivity of the coupled ocean-atmosphere system to future changing boundary conditions may be uncertain (DiNezio et al., 2012). Alternatively, model-based recent studies demonstrate projected changes toward more extreme ENSO occurrences under greenhouse warming (Cai et al., 2013; Power et al., 2013). Investigations of the sensitivity of ENSO to anthropogenic climate change are also restricted by the relatively short instrumental record, which provides us with limited guidance for understanding the range of ENSO behaviours. For example, the observed changes in the character of ENSO in the 20th and 21st centuries (including dominance of El Niño, rather than La Niña, episodes from the mid-1970s and La Niña-like mean state since the 1990s (England et al., 2014)) are difficult to evaluate in terms of a forced response or unforced variability given the limited observational record almost certainly does not capture the full range of internal climate dynamics.")

Page 1589 on inter-decadal modulation of ENSO behaviour, one relevant paper is Borlace et al. 2013, J. Climate that demonstrate how this can arise naturally via vacillation of the internal ENSO dynamics.

- This reference has been added.

Fig 1. : The Y-axis ticks do not look correct, and the western and central boxes are not centred about the equator.

- This has now been corrected in the revised multi-model Figure 1 and Figure 2.

P1584 (20, 25, etc.) "past 1000" should be "past-1000" or "past1000". Otherwise 'past 1000 simulations' could be mistaken as one thousand simulations in the past, while it should mean past 1000-yr simulations.

- This is an artifact of typesetting, not error.

P1584 (25) Refer to Fig. S2 and Fig.... How about showing observations as well?

- A reference to Supplementary Figure 4 has now been included. As this figure now shows past1000 time series, observations have not been added.

10 'categorised' should be 'categorise'

- This has been corrected.

p.1585 (15), "experiments in was" delete 'in'

- This has been corrected.

"For the GISS-E2-R (Schmidt et al., 2014) and IPSL-CM5A-LR (Dufresne et al., 2013) models...." It is better to insert these reference in Table 1 for all of the models.

- These references have been removed, but not added to Table 1, as no specific model is discussed here, but rather the combined contributions to CMIP5.

Reviewer 3
Main points

1.1 Scope

It seems that the goal of the paper is to evaluate the extent to which the potential nonstationarity of teleconnections for proxy-based reconstructions of ENSO. As such, there should be a more extensive review of such work. A non-exhaustive list would be: Stahle et al. [1998]; Braganza et al. [2009]; Wilson et al. [2010]; McGregor et al. [2010]; Emile-Geay et al. [2013a,b]; Li et al. [2011, 2013], few of which are acknowledged here.

- The goal of this paper is to evaluate the potential nonstationarity of teleconnections of ENSO from proxy reconstructions in regions where ENSO inferences have been made from single locations. We recommend that multi-dimensional information in the form of spatial patterns of change through time should be considered. We now included a more extensive discussion of such multi-proxy reconstructions, including several of the referenced studies above, in section 6.

It also would seem natural to pick (at least) one of the networks used above and see how vulnerable they are to the changes in teleconnections identified in the paper, on the context of pseudoproxy experiments [PPEs Smerdon, 2011]. One wouldn't have to use fancy reconstruction methods for this: an analysis of the signal-to-noise ratio in the network and how it changes from century to century would be all that is needed.

- This was not within the scope of our present study, which specifically aimed to investigate three regions using experiments with varying forcings. We would welcome the opportunity to investigate changes in teleconnection in pseudo-proxy experiments. We would gladly collaborate with the review on a study focusing on this suggestion.

On the topic of literature review, the authors should include more on volcanic effects on ENSO [Timmreck, 2012, and references therein].

- A detailed discussion of volcanics is now provided in section 6, including reference to Timmreck, 2012.

The section on ENSO characteristics (4.1) would do well to acknowledge the considerable work that has already been done to characterize ENSO in CMIP5/PMIP3 models. In particular Ault et al. [2013] showed that piControl simulations are incompatible with a suite of recent reconstructions [Emile-Geay et al., 2013a,b], while forced simulations are compatible, but seem to show a different phase relationship to the forcing. Also refer to Karnauskas et al. [2012] for a centennial-scale, ENSO-like oscillation that arises internally.

- We now include reference to Karnauskas et al 2012 and include discussion of previous work examining control and last millennium simulations in section 6.

1.2 Mechanisms

The main point of models is the ability to diagnose the causes of climate change. In this case, what makes teleconnections wobble, and is this robust across models? Do we expect the mechanism(s) to be stronger or weaker in nature?

- It is unclear what comparison is being suggested here. Are the models stronger or weaker in nature than *what/where*? In this study, the models are not used to diagnose the causes of climate change, but rather to investigate, as stated, whether proxy archives in the tropical Pacific are likely to be recording alterations in ENSO base frequencies or local-scale teleconnections under differing boundary conditions. We now suggest that such diagnosis of mechanisms would make a useful future study ("Furthermore, our present study did not comprehensively investigate the relative influences on various external forcings (solar and volcanics) and internal variability on ENSO characteristic, which would provide useful information for comparison with proxy records. These mechanisms could be investigated, for example, using a suite of simulations with single or varying forcings.")

1.3 Statistical Considerations

Reference period It is good that the authors considered 100-year epochs within the past1000 ensemble, but it would have been logical to use a 100-year reference window for the historical or piControl simulations as well. I am surprised that they chose a 40-year span (1976-2006) and wonder how the results would change if they lengthened this reference period. For instance, the authors state "Although ENSO surface temperature anomalies across the Pacific are qualitatively similar, anomalies associated with the historical period (1976–2005) are generally of greater magnitude, particularly at remote locations outside the equatorial Pacific, including over North America and the south Pacific. These differences in magnitude between the Last Millennium and the historical may relate to the differing boundary conditions during the historical period associated with anthropogenic forcings, such as long-lived greenhouse gases, or simply from the greater diversity of ENSO episodes represented in the longer Last Millennium simulation." (emphasis mine). They need to rule out that this is not a sampling artifact due to comparing 100-year epochs to a 40y-long one.

- We have now included a 100 year historical period for analysis.

Statistical tests the Kolmogorov-Smirnov test is widely used to compare distributions, and I have no issue with its use here. I would only point out that the price of it not making distributional assumptions is that it has relatively low power. If the datasets are Gaussian, the authors may be better served by other tests that make this assumption, especially if they mainly intend to detect changes in location or scale. Note that precipitation is notoriously non-Gaussian, but can be made Gaussian via a transformation (cf the Standardized Precipitation Index, or SPI). Significance One of the most persistent problems in our field is that statistical tests are carried out assuming IID (independent and identically-distributed) data, which in many cases is not verified. Indeed, persistence from month to month or year to year often drastically reduces the number of degrees of freedom available for a test [Wilks, 2011]. Did the authors account for autocorrelation in tests presented in Fig. 4? Also, in Fig. 8, how significant are the variations in correlation? In many cases they look well within sampling error to me. It is imperative that the authors quantify this, because it is one of their main results ("it is evident in the model experiments that differing teleconnections may result at different points in time and may differ from present-day relationships"), and it may well evaporate in the face of statistical rigor. Do the correlations change sign altogether? How much would this bias a multiproxy reconstruction of ENSO?

- We did not account for autocorrelation in Figure 4. However, we have now included statistical significant in Figure 7/8 and accordingly in the text.

Wavelet spectra It should be noted that the Morlet wavelet spectrum as implemented by Torrence and Compo [1998] does not conserve energy, hence is not fit for spectral analysis [Liu et al., 2007]. The authors need to use the correction proposed in the latter paper and redo Fig. 2.

- On recommendation of all reviewers, we have reduced the length of the manuscript and focused on changes in the ENSO-local relationships through time. We have also removed the morlet wavelet spectrum plots.

1.4 Combining proxies

The idea to use multiple proxies to average out noise is nothing new. Few people will disagree with the authors when they write "We argue that proxy insights into change and variability in ENSO system are likely to be most robust when evidence is be synthesised over large spatial areas [...] considering multi-dimensional information in the form of spatial patterns of change through time is likely to yield more robust insights in large-scale systems."

While there could be many ways of synthesising evidence over large spatial areas, it seems that the authors have in mind the usual compositing, since they cite Li et al. [2013] as an example thereof. The authors should be aware that dating uncertainties may complicate this matter a great deal. Indeed, Comboul et al. [2014] showed that linear combinations of time-uncertain proxies may considerably distort the spectrum of the signal reconstructed from them. For certain diagnostics, like variance, McGregor et al. [2013] argued that one should first compute those diagnostics locally, prior to compositing. I ask that the authors acknowledge this work, and perhaps other efforts, to provide more specific guidance as to how one should synthesise evidence over large spatial areas in the real world. Such things are much trickier with real proxies than with gridded, exactly-dated GCM output.

- We do not suggest that multiple proxies should be averaged, and nor that we should "average out noise". We argue that using one location alone makes it difficult to determine where local, remote or teleconnected changes have occurred. The authors have considerable experience with generating palaeoclimate records and understand the limitations of dating material. We do not agree that the difficulties of generating proxy records means that interpretations that are not based of best practice are warranted. Furthermore, we have made specific recommendations that ENSO-related interpretations from remote sites "should be considered in conjunction with palaeo-reconstructions from within the central Pacific basin, the so-called "centre of action" of ENSO (Cobb et al., 2013)."

2 Editorial comments

The writing style is often long-winded. In many cases, this is because the authors are handwaving instead of basing their arguments on solid, quantitative proof. It is also rather imprecise and there are numerous omissions, some of which are pointed out here. A revised version should tighten up the writing.

- The specific recommendations detailed below have been included into the revised manuscript. Furthermore, we have attempted to make the writing more succinct. However, with few specific points of contention provided by the reviewer in terms of this comments, and the two other reviewers commenting that the manuscript is well written, these comments about handwaving and long-winded writing are very difficult to address explicitly.

1. "The MIROC-ESM model is excluded from this analysis as it exhibits large drift related error in the form of long-term trends that cannot be attributed to natural variability, but instead relate to deficiencies in model physics and numerics (Gupta et al., 2013) (Fig. 3)." (p1587, bottom) needlessly repeats p1584 L 29.
   - This repetition has been removed from Section 3.

2. p1584 L26 "its representation of ENSO spectra is too short": improper terminology. Just say that ENSO is two biennial in this model, or that its dominant periodicity is too short. A spectrum is neither short nor long.
   - This has been changed to read "One model (bcc-csm1-1) was excluded from analysis because its dominant ENSO periodicity is too short (Supplementary Fig. 4)."

3. p1588 L16-17 "compared with observed" change to "compared with observations"
   - This has been changed.

4. p1589 L 16 "In the historical,..." . In the historical what?
   - This has been corrected to say "historical experiment"

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> would provide further insight into the apparent complexity of ENSO impacts through time.")

6. The Bellenger et al reference has all author names duplicated : Bellenger, H., Bellenger, H., Guilyardi, E., Guilyardi, E., Leloup, J., Leloup, J., Lengaigne, M., Lengaigne, M., Vialard, J., and Vialard, J.: ENSO representation in climate models: from CMIP3 to CMIP5, Clim. Dynam., 42, 1999–2018, doi:10.1007/s00382-013-1783-z, 2013. Please check other references for similar mistakes.
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Stability of ENSO and its tropical Pacific teleconnections over the Last Millennium

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Abstract

Determining past changes in the amplitude, frequency and teleconnections of the El Niño-Southern Oscillation (ENSO) is important for understanding its potential sensitivity to future anthropogenic climate change. Palaeo-reconstructions from proxy records can provide long-term information of ENSO interactions with the background climatic state through time. However, it remains unclear how ENSO characteristics have changed on long timescales, and precisely which signals proxies record. Proxy interpretations are typically underpinned by the assumption of stationarity in relationships between local and remote climates, and often utilise archives from single locations located in the Pacific Ocean to reconstruct ENSO histories. Here, we investigate the long-term characteristics of ENSO and its teleconnections using the Last Millennium experiment of CMIP5 (Coupled Model Intercomparison Project phase 5) (Taylor et al., 2012). We show that the relationship between ENSO conditions (NINO3.4) and local climates across the Pacific basin differs significantly for 100-year epochs defining the Last Millennium and the historical period of 1906-2005. Furthermore, models demonstrate decadal- to centennial- scale modulation of ENSO behaviour during the Last Millennium. Overall, results suggest that the stability of teleconnections may be regionally dependent and that proxy climate records may reveal complex changes in teleconnected patterns, rather than large-scale changes in base ENSO characteristics. As such, proxy insights into ENSO may require evidence to be considered over large spatial areas in order to deconvolve changes occurring in the NINO3.4 region from those relating to local climatic variables. To obtain robust histories of the ENSO and its remote impacts, we recommend interpretations of proxy records should be considered in conjunction with palaeo-reconstructions from within the central Pacific.

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1. Introduction

The El Niño-Southern Oscillation (ENSO) is an important determinant of climate variability, altering global rainfall patterns and modulating global temperatures. Understanding the long-term characteristics of ENSO variability and its sensitivity to external forcings, such as greenhouse gases, represents a fundamental climate modelling and data challenge. While changes in ENSO behaviour may occur under future global warming (Power et al., 2013), previous studies indicate a large dispersion in global climate model (GCM) projections of changes in ENSO characteristics (e.g. Collins et al., 2010; Vecchi and Wittenberg, 2010), and hence the sensitivity of the coupled ocean-atmosphere system to future changing boundary conditions may be uncertain (DiNezio et al., 2012). Recent model-based studies suggest changes toward more extreme ENSO occur under future greenhouse warming (Power et al., 2013; Cai et al., 2014). However, investigations of the sensitivity of ENSO to anthropogenic climate change are restricted by the relatively short instrumental record, which provides us with limited guidance for understanding the range of ENSO behaviours. For example, the observed changes in the character of ENSO in the 20th and 21st centuries (including dominance of El Niño, rather than La Niña, episodes from the mid-1970s, and a La Niña-like mean state since the 1990s (England et al., 2014)) are difficult to evaluate in terms of a forced response or unforced variability given the limited observational record almost certainly does not capture the full range of internal climate dynamics.

High resolution palaeo-reconstructions, including from tree rings, sediment cores, corals and speleothems, have the potential to provide long-term information about changes in modes of climatic variability and their sensitivity to different boundary conditions. Some tropical proxy records reveal ENSO interactions with the background mean climatic state. For example, data from long-lived fossil corals are often interpreted quantitatively as estimates of ENSO changes through time that show a range of ENSO frequencies and amplitudes through time. Central Pacific coral reconstructions generally reveal a weakened ENSO during the early Holocene (McGregor et al., 2013) and highly variable ENSO activity throughout the Holocene (Cobb et al., 2013), which may have arisen from internal ocean-atmosphere variability (Cobb et al., 2003). Developing robust estimates of natural ENSO variability over a period longer than permitted through the instrumental record is a useful research avenue, with the potential for informing meaningful adaptive strategies for future climate change.

Palaeo-ENSO proxy records of the Last Millennium (1,000 years) are sparsely populated temporally and spatially, and reconstructions remain uncertain (Cobb et al., 2003; Khider et al., 2011). It also remains unclear as to precisely which climatic signals associated with ENSO are being recorded in these individual proxy records and whether these provide the necessary resolution to reconstruct ENSO changes. The assumption of stationarity of relationships between local and remote climates (teleconnections) underpins the interpretation of many palaeoclimate reconstructions, although stationarity should not necessarily be assumed in terms of ENSO variability (Gallant et al., 2013). Are palaeo-reconstructions from the tropical Pacific recording base changes in the ENSO system or rather changes in teleconnected patterns? Previous model-based studies have identified sensitivity in the

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relationship between ENSO and the background climate state, and urged caution in the reconstruction of ENSO from proxy records under the assumption of stationarity of observed teleconnections (Coats et al., 2013; Gallant et al., 2013).

However, these studies have not comprehensively addressed the degree to which uncertainty about the non-stationarity of ENSO teleconnections can be assessed for particular locations and for particular mean climatic states. Furthermore, although we previously investigated the potential non-stationarity of hydrologic responses to ENSO-like conditions under disparate boundary conditions in idealised model simulations, we did not provide guidance for interpreting tropical proxy records in particular regions (Lewis et al., 2014), which currently comprise our dominant source of information about ENSO characteristics beyond the instrumental record. In addition, while previous studies have utilised proxy records, together with simulations using global climate models (GCMs) to evaluate the representation of ENSO in the current generation of GCMs (Cobb et al., 2013), these approaches focused on using palaeo-ENSO reconstructions to test the performance of GCMs for the purpose of constraining uncertainty in future projections of ENSO behaviour under climate change.

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As such, precisely which expressions of ENSO are being recorded in proxy archives under differing climatic boundary conditions have not been comprehensively interrogated. Climate models, in addition to observational and proxy climate evidence, allow an understanding of long-term ENSO changes through time to be obtained (Schmidt, 2010). A new generation of climate models and experiments has recently become available (Taylor et al., 2012), providing an opportunity for the first time to investigate ~1200 years of ENSO variability and establish a framework for understanding ENSO changes through time, using more models than previously possible. Hence in this current study, we investigate changes in ENSO characteristics (frequency and amplitude) in model experiments of the Last Millennium (‘past1000’). Focusing on three key climatic regions (East, Central and West Pacific), where explicit palaeo-ENSO reconstructions have been made, teleconnected patterns (the relationship between local and remote climates) throughout the Last Millennium are examined for surface temperatures and precipitation. We ultimately aim to determine whether proxy archives in the tropical Pacific are likely to be recording alterations in ENSO base frequencies or local-scale teleconnections under differing boundary conditions.

2. Datasets and methods

2.1 Definitions

The study is primarily focused on palaeo-ENSO variability from the tropical Pacific. Model data were investigated in three regions that have been identified as sensitive to modern ENSO variability and have also been used explicitly to reconstruct past ENSO changes (e.g. Cobb et al., 2013; McGregor et al., 2013). Area-mean anomalies for precipitation and surface temperature were calculated for the West (10ºS-10ºN, 105º-155ºE), Central (10ºS-10ºN, 170º-130ºW) and East Pacific (20ºS-5ºN, 65º-90ºW) region and surface temperature for the NINO3.4 region (5°N - 5°S, 170° - 120°W) (Fig. 1). These regions are not intended to provide exhaustive coverage of ENSO impacts, but are large enough to provide useful comparisons with model-based data.

El Niño episodes were defined based on simulated surface air temperature anomalies in the NINO3.4 region, with events defined in the models when NINO3.4 temperature anomalies were >0.5 K for at least six consecutive months (Trenberth, 1997). Conversely, La Niña episodes were defined when NINO3.4 temperature anomalies were <-0.5 K for at least six consecutive months. Spatial patterns are examined by compositing monthly temperature and rainfall anomalies into positive (El Niño) and negative (La Niña) phases using these definitions for all CMIP5 models analysed (Figs 1 and 2). We utilise the NINO3.4 region as an index to classify ENSO conditions. Although the NINO3.4 region is commonly used to categorise ENSO episodes, it should be noted that there are other indices of ENSO that may also provide useful information beyond the central tropical Pacific conditions described by the NINO3.4 (see Supplementary Figs 1-3).

2.2 Model experiments

CMIP5 data (Taylor et al., 2012) were downloaded from the Project for Model Diagnosis and Intercomparison (PCMDI) through the Australian Earth System Grid (ESG) node. Simulations were used of the historical (1850-2005 CE) experiment, which is forced using changing atmospheric compositions due to observed anthropogenic and volcanic influences, solar forcings and emissions of short-lived species from natural and anthropogenic aerosols. In addition, simulations were used of the Last Millennium (past1000) (850-1849 CE), in which reconstructed time evolving exogenous forcings are imposed, including changes in volcanic aerosols, well-mixed greenhouse gases, land use, orbital parameters and solar changes. Each model's pre-industrial control simulation (piControl) with non-evolving pre-industrial forcings was analysed.

Data (precipitation (pr) and surface temperature (ts)) for six remaining models were regridded onto a common 1.5° latitude by 1.5° longitude grid. For the piControl and past1000 experiments, monthly anomalies were calculated by subtracting the mean seasonal cycle for each model. For the historical experiment the 100-year period of 1906-2005 is considered. Additional experiments were analysed for CMIP5-participating models, where available. For GISS-E2-R and IPSL-CM5A-LR models, extended control simulations of >500 years in duration were analysed and compared to forced, past1000 experiments.

2.3. Models and evaluation

The basic properties of El Niño-Southern Oscillation (ENSO) simulated in Coupled Model Intercomparison Project phase 5 (CMIP5) models (Taylor et al., 2012), relative to observations, have been comprehensively evaluated in previous studies (e.g., Bellenger et al., 2013; Guilyardi et al., 2012). For example, Bellenger et al (2013) examined ENSO through 6 metrics - 1) ENSO amplitude (Niño3 sea surface temperature (SST) standard deviation), 2) structure (Niño3 vs. Niño4 amplitude), 3) frequency (root mean square error of Niño3 SST anomaly spectra), 4) heating source (Niño4 precipitation standard deviation), 5) the amplitude of the ENSO biennial component (the ratio of the Niño3 SST anomaly timeseries power in the 3–8 years and 1–3 years bands) and 6) seasonality of ENSO (ratio between winter November-January over spring March– May average Niño3 SST anomalies standard deviations. This study showed a significant improvement in model skill compared

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with CMIP3 generation models, including improved sea surface temperature anomaly location, seasonal phase locking and ENSO amplitude.

In our current study, all CMIP5 models were analysed where past1000 simulations were archived on the Australian ESG node. This provided nine models for selection, although bcc-csm1-1 was excluded from analysis because its dominant ENSO periodicity is too short and MIROC-ESM model was also excluded, as it exhibits large drift related error in the form of long-term trends that cannot be attributed to natural variability (Gupta et al., 2013) (see Supplementary Fig. 4). We use the remaining seven models with CMIP5 Last Millennium simulations (see Table 1). For GISS-E-2-R, we include only one contributing realisation (r1i1p121) to constitute a multi-model ensemble of one member from each model.

Models were compared to twentieth century reanalysis data (20CR) (Compo and Whitaker, 2011), which is widely used a proxy of observed climate (King et al., 2014; Klingaman and Woolnough, 2013). In order to focus on ENSO characteristics, we compare these datasets for the period of 1976-2005, rather than an extended historical period, due to greenhouse forced non-stationarities over the post-industrial era. It should be noted that ENSO properties have changed over the last several decades, in particular with increased frequency of Central Pacific-centred events in recent decades, which have substantially different characteristics (Pascolini-Campbell et al., 2014). Hence model skill in recent decades does not ensure that all 'flavours' of ENSO are equally well captured. CMIP5 historical simulations were compared to reanalysis precipitation and surface temperature over the 1976-2005 period for several ENSO-related characteristics.

To investigate the model representation of ENSO spatial patterns, the first empirical orthogonal function of the tropical Pacific surface temperature anomalies was calculated for 20CR reanalysis and CMIP5 multi-model mean (MMM) EOF (Figs 3a and 3b). Precipitation anomalies were also analysed (Figs 3c and 3d). Surface temperature and precipitation patterns are qualitatively similar for reanalysis and models; temperature patterns are generally of the same sign, although the meridional width of tropical temperature anomalies is narrower than in the reanalysis estimates, and simulated precipitation patterns are similar to the reanalysis estimate in the central Pacific, although positive anomalies are located too far westward in the CMIP5 MMM, compared with observations. In addition, the relationship between NINO3.4 surface temperature anomalies and global precipitation fields in reanalysis was compared to the CMIP5 MMM (Figs 3e and 3f). The correlation coefficients between NINO3.4 temperature anomalies and local precipitation are generally of the same sign in simulated and reanalysis fields, including positive correlations in the Central and East Pacific and negative correlations in the west Pacific. These reanalysis-model comparisons are broadly insightful about the model representations of ENSO.

3 Diagnosing ENSO changes and teleconnections

The location of ENSO activity in the historical and Last Millennium experiments was first explored using the leading empirical orthogonal function (EOF) of the tropical Pacific surface temperature. These spatial patterns were compared to the NINO3.4 index to determine possible non-stationarities

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in the site of ENSO activity through time (Li et al., 2011). This EOF analysis (Supplementary Fig. 5) demonstrates that in both experiments, the surface temperature patterns are loaded in the NINO3.4 region. Although there are some differences in the spatial patterns of the leading EOF mode across the equatorial Pacific, the similarity in model experiments in this particular region indicates that areal-average NINO3.4 temperatures provide a useful metric of ENSO activity in both experiments. An EOF analysis does not necessarily reveal modes that can be readily interpreted physically. However, in this study utilise an identical set of models for each experiment, and hence possible biases in ENSO representations in the models are not considered prohibitive to investigating changes in the stability of teleconnections through time.

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A wavelet analysis was next used to examine the frequency and amplitude of NINO3.4 surface temperature variability in each model for statistically significant changes. Wavelet analysis is useful for examining non-stationary signal and provides time and frequency localisation. A Morlet mother wavelet (Torrence and Compo, 1998) with degree 6 was used to calculate the wavelet power spectra and identify large-scale changes in variance. Wavelet spectral estimates were tested against red noise, represented as a first order autoregressive process. The NINO3.4 mean wavelet power spectrum, generated using a Morlet wavelet of degree 6, was used as a metric for ENSO amplitude. The spectral power was calculated for the historical simulation (years 1906-2005) and compared to the range of spectral power displayed in the past1000 experiment, calculated using ten 100-year epochs (Fig. 4).

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The relationship between ENSO variability and teleconnected patterns in the tropical Pacific regions (East, Central and West) was diagnosed through several complementary approaches. First, an ordinary least squares regression between monthly NINO3.4 mean surface temperature and remote area-mean surface temperature, and between monthly NINO3.4 mean surface temperature and remote area-mean precipitation was compared for the historical and Last Millennium experiments, for each region. Second, the relationship between local and NINO3.4 climates was considered using the correlation between variables (Corr(Local, Remote), analogous to considering land-surface coupling strength (Lorenz et al., 2012). Correlations coefficients were calculated for monthly timeseries in ten 100-year epochs comprising the Last Millennium. Values were determined at each model gridbox and an area-weighted mean calculated for each region. The significance of correlations was assessed at the 95% confidence level for each coefficient using a t-test. Third, the significance of identified changes in local-remote relationships during the Last Millennium was investigated.

For each 100-year epoch comprising the Last Millennium, the El Niño- and La Niña- associated local temperature and precipitation anomalies were selected for each region. A two-sided Kolmogorov-Smirnov (KS-) test was used to investigate whether the distribution of local climate variables in 100-year epochs within the Last Millennium could statistically have been drawn from the same population (at the 5% significance level). A two-sided KS-test was applied to each ENSO phase for each variable (surface temperature, precipitation) in each region (East, Central, West) comparing every permutation of epochs sequentially (e.g. comparing El Niño-associated Central Pacific temperatures during 850-949 with 950-1049, then 1050-1149, then 1150-1249 etc.). A KS-test was used for detecting changes in ENSO-remote climate relationships in Last Millennium timeseries as it is non-parametric and requires no assumptions to be made regarding the distribution of the data. A change is detected where the null hypothesis (that the distributions considered were drawn from the same population) is rejected at the 5% significance level.

4. ENSO during the Last Millennium

4.1 ENSO characteristics

Models demonstrate a range of variance in the ENSO-relevant band (2-8 years) for the historical experiment (Fig. 4). In the historical experiment, ENSO amplitude is generally weaker at relevant periods for the MRI-CGMC3, GISS-E2-R and HadCM3 models. Notably, the amplitude of higher ENSO-relevant periods (6-8 years) in the historical simulations is generally outside the range exhibited in the Last Millennium for each model (Fig. 2). However, previous model-based studies (Coats et al., 2013; Wittenberg, 2009) that reveal strong inter-decadal to inter-centennial modulation of ENSO behaviour warn that such modulation may not be fully revealed by the comparatively short instrumental climate record available. Hence, large uncertainties may exist in ENSO metrics diagnosed from short records.

Decadal- to centennial-scale El Niño- and La Niña-like episodes during the Last Millennium simulations are evident in all models analysed here (Fig. 5). This low frequency modulation may result from internal variability (e.g., Karnauskas et al., 2012; Borlace et al., 2013), or may be relate to external forcings. For example, external forcings from large tropical volcanic eruptions occurring between 1250 and 1600 CE (Supplementary Fig. 6), may produce decadal- to centennial-scale ENSO responses, which are discussed further in section 6. Alternatively, decadal- to centennial-scale modulation of ENSO behaviour may result from internal ocean-atmosphere dynamics rather than a response to exogenous forcings. The properties of ENSO simulated in the control simulations (Fig. 6) that do not impose external forcings, exhibit qualitatively similar variability to that shown in the externally forced Last Millennium experiment (Fig. 5). This similarity includes multi-decadal to centennial- scale El Niño- and La Niña-like phases.

4.2 ENSO impacts and teleconnections

Models show broadly similar global impacts associated with NINO3.4 regional temperature anomalies in the Last Millennium and historical experiments (Figs. 1 and 2). The composited patterns of global surface air temperature anomalies associated with positive (El Niño) and negative (La Niña) ENSO phases derived from all analysed models spatially coherent across the experiments. However, both El Niño and La Niña anomalies associated with the historical period (1906-2005) are generally of greater magnitude than for the Last Millennium, for the MMM and in various models including FGOALS-s2 and CCSM4. These experiments are most similar in the tropical Pacific, with larger differences evident at remote locations outside the equatorial Pacific, including over North America and the south Pacific.

The relationship between NINO3.4 regional temperature anomalies and the mean local climate is examined in each analysed Pacific region (East, Central, West) using the correlation between

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variables (Corr(Local, Remote). This approach is analogous to considering land-surface coupling strength (Lorenz et al. 2012). We diagnose temporal stability using this correlation in ten 100-year epochs that comprise the Last Millennium and the 100-year historical period of 1906-2005 (Figs 7 and 8). The strength of the remote-local relationship varies temporally and is also both regionally and climate variable dependent. In the West Pacific, particularly, this coupling is generally weak and not found to be statistically significant for most epochs and models. It is notable that the strongest West Pacific-NINO3.4 correlation for the MMM, and FGOALS-s2 and IPSL-CM5A-LR models is calculated for the historical experiment. There is, however, a large dispersion in correlations calculated across the models, with negative correlations calculated from CCSM4, which also shows the strongest El Niño-related cool features in the Warm Pool region (Figs 1 and 2). The remote- local temperature relationship is consistently stronger in the East and Central Pacific regions. The strongest local precipitation coupling occurs for the Central Pacific, with no statistically significant relationships found for the West and East Pacific across the model ensemble (with the exception of CCSM4) (Fig. 8).

We also investigate the significance of identified Last Millennium changes in local-remote relationship across these epochs. A Kolmogorov-Smirnov (KS) test was used to determine whether the distributions of El Niño- and La Niña- associated local temperature and precipitation anomalies in each region in 100-year Last Millennium epochs could statistically have been drawn from the same population. There are detectable differences (at the 5% significance level) in the distribution of ENSO-associated local climate variables in these 100-year epochs. West Pacific El Niño- and La Niña- associated temperatures, for example, significantly vary in character through the Last Millennium and with the historical 100-year epoch for the multi-model mean. Temporal changes in local ENSO fingerprints (Corr(Local, Remote) of the Last Millennium, also likely result from external forcings and/or internal ocean-atmosphere dynamics, which are discussed further in section 6. However, these same relationships were not explored in the extended control simulations because of the small number of contributions available from different models. Differing teleconnections may result at different points in time and may also differ from present-day relationships. In addition, Last Millennium variability in ENSO-local climate relationships across sites in the tropical Pacific suggests that global ENSO changes do not necessarily scale linearly to local scales and cannot be assumed to do so.

5. ENSO under differing boundary conditions

The CMIP5 archive also provides simulations of the mid-Holocene (midHolocene, circa 6,000 years ago) from multiple participating climate models. The mid-Holocene provides a well-constrained target for model-based studies (Schmidt et al., 2004) with substantially larger time-evolving forcings than those imposed during the Last Millennium, and this period has also been the target of palaeo-reconstructions. Hence, these simulations are also briefly investigated here, in addition to the information provided by the Last Millennium experiment. Mid-Holocene simulations are run for at least 100 years after reaching equilibrium and have changed orbital parameters and atmospheric concentrations of greenhouse gases imposed. Other boundary conditions such as aerosols, solar constant, vegetation and topography are prescribed as the same as in the pre-industrial control

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simulation. We note that although the limited 100 model years contributed by various models may not provide an exhaustive representation of ENSO behaviour in the mid-Holocene, they nonetheless provide valuable insight into the potential influences of varying boundary conditions.

By way of context, Cobb et al. (2013) report that central Pacific corals record highly variable ENSO activity through the Holocene, although no systematic trend in ENSO variance was demonstrated in this study. A complementary Central Pacific reconstruction from Kiritimati Island suggests that ENSO variance was persistently reduced by 79%, compared with today at this location about 4,300 years ago (McGregor et al., 2013). Central Pacific coral-based evidence of ENSO variability is substantially different from lower-resolution records from the eastern equatorial Pacific (Conroy et al., 2008; e.g. Moy et al., 2002). Collectively, East Pacific records suggest a systematic decrease in mid-Holocene ENSO variance. On the West Pacific side of the basin, corals from northern Papua New Guinea reveal a reduction in ENSO frequency and amplitude over the period of 7.6-5.4 ka (thousand years ago) compared with today, and also identifies large and protracted El Nino events for 2.5–1.7 ka (McGregor and Gagan, 2004). These Mid-Holocene ENSO reconstructions do not necessarily provide contradictory information, but may instead reflect geographic complexities (Carre et al., 2014; Cobb et al., 2013). However, as proxy-based reconstructions from each of these regions have been used to infer changes in the same coupled ocean-atmosphere system, we also examine teleconnected ENSO patterns under these significantly different boundary conditions that characterise the mid-Holocene.

In this study, we consider the subset of participating CMIP5 models with contributions of mid-Holocene simulations (MRI-CGCM3, IPSL-CM5A-LR, FGOALS-s2, CCSM4) and find a general reduction in spectral power across ENSO-relevant frequencies that has also been reported in model experiments of this period conducted prior to the release of CMIP5 (Chiang et al., 2009). This reduced spectral power in the ENSO band can be considered a metric for reduced ENSO amplitude (Stevenson, 2012). Previous model and proxy-based studies have also hinted at subdued ENSO activity in the mid-Holocene. For example, early studies using simple numerical models of the coupled ocean-atmosphere system by Clement et al. (2000) demonstrate increasing ENSO variability throughout the Holocene in response to time varying orbital forcings. The impact of mid-Holocene orbital changes on ENSO variability has not been demonstrated comprehensively from proxy records. However, various fossil coral reconstructions indicate that there may have been reductions in ENSO variability in the mid-Holocene (Cobb et al., 2013).

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In addition, when CMIP5 midHolocene model data are composited into positive (El Niño) and negative (La Niña) phases, the magnitude of simulated mid-Holocene spatial patterns of ENSO impacts (Supplementary Fig. 6) are subdued, relative to the historical. The relationship between NINO3.4 mean surface temperature anomalies and regional (East, Central, West Pacific) temperature and precipitation was also examined and shows particularly that the relationship between West Pacific surface temperature anomalies and corresponding NINO3.4 temperature anomalies differs from the midHolocene and historical simulations. The frequency of high and low local surface temperature anomalies in the West Pacific during El Niño defined conditions is reduced in the midHolocene

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experiment compared with the historical. The NINO3.4 impacts on East and Central Pacific regional temperatures are broadly similar for the historical and mid-Holocene.

6. Towards reconstructing robust ENSO histories

This study uses palaeoclimate simulations conducted using a suite of CMIP5-participating models with various forcing to investigate changes in ENSO and its teleconnections under differing boundary conditions (the Last Millennium and mid-Holocene). The models show broadly similar global impacts associated with NINO3.4 temperature anomalies between the Last Millennium and historical experiments, although the magnitude of anomalies in the historical simulation is generally larger. We find that ENSO-local climate relationships are typically weak in the West Pacific region, with remote-local temperature relationships consistently stronger in the East and Central Pacific regions. The relationships between NINO3.4 and local precipitation are weak and found to be significant only in the Central Pacific. Furthermore, in the West Pacific particularly, El Niño- and La Niña- associated temperatures vary significantly in character throughout the Last Millennium and with the historical 100-year epoch.

Previous studies of ENSO variability over the period encompassed in the CMIP5 past1000 simulations suggest that the most robust ENSO influence occurs over the Maritime Continent, in the western part of the Pacific basin (Li et al., 2013). Overall, ENSO teleconnections over the pan-Pacific region were found to be generally stronger when ENSO variance is higher. In our present study, we find, conversely, that the correlation between West Pacific climates and NINO3.4 is lower than for the Central and East Pacific, and also most variable between epochs. This apparent mismatch has several possible causes. First, Li et al. (2013) focused on tree ring records, and the Maritime Continent region they describe lies to the west of the West Pacific region we define to encompass published coral records. This is likely an important difference in definition, due to the subtle shifts in the western extent of the warm tongue characterising positive (El Niño) episodes, and conversely to the cool anomalies charactering La Niña episodes. Furthermore, simulated climates of the Warm Pool region are likely highly sensitive to model bias (Brown et al., 2012; 2013) and hence model dispersion is expected (e.g., CCSM4 model in Fig. 7). Hence, subtle changes in the Pacific basin may impact this region through several ocean-atmosphere mechanisms.

Although our current results appear to contradict those previously reported on ENSO teleconnections (e.g., Li et al., 2013), collectively these studies suggest that remote reconstructions of ENSO require a regional perspective. It may be inherently difficult to deconvolve variability in the NINO3.4 region and local-scale, teleconnected climatic change in remote regions. Palaeoclimate studies often utilise archives from single locations located in the Pacific Ocean to reconstruct generalised basin-scale histories of ENSO. However, multiple studies demonstrate that proxies in one location alone should not be considered regionally representative, or singularly insightful about robust ENSO reconstructions without explicit examination of the stability of ENSO teleconnections. We argue that proxy insights into change and variability in ENSO system are likely to be most robust when evidence is be synthesised over large spatial areas. That is, only incomplete information about temporal

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changes in a large-scale climate system can be provided by considering changes at a singular location (i.e. a time series of a climatic variable).

Considering multi-dimensional information in the form of spatial patterns of change through time is likely to yield more robust insights in large-scale systems. This provides a framework for enhanced interpretations of the invaluable information of palaeoclimatic change provided by proxy records. For example, combined evidence from the West and Central Pacific is more likely to reveal the potentially subtle changes in ENSO-associated spatial patterns of temperature and precipitation perturbations across the Pacific. For remote regions outside the equatorial Pacific, the non-stationarity of ENSO teleconnections is likely to be more problematic. These sites should be considered in conjunction with palaeo-reconstructions from within the central Pacific basin, the so-called "centre of action" of ENSO (Cobb et al., 2013). Under boundary conditions significantly different from present, such as the mid-Holocene ENSO teleconnections are likely to be more variable, and hence potential non-stationarities in local-remote relationships require explicit consideration in proxy interpretations. Spatially integrated approaches have already been undertaken and provide valuable information over the recent past (e.g. Li et al., 2013), and several multi-proxy reconstructions of ENSO are now available (e.g., Braganza et al., 2009; Wilson et al., 2010, Emile-Geay et al., 2013a; 2013b). Although these are often limited in terms of temporal coverage to the past few centuries, or derived from extratropical record and hence not directly representative of ENSO variability, they provide highly valuable records of aspects of the ENSO system.

In this study, we investigated teleconnected changes using NINO3.4 to represent ENSO, which was based on the determined similarity of the leading EOF of the multi-model mean in the historical and Last Millennium simulations. However, important spatial changes in ENSO patterns are known to occur and have been identified over the observational period (McPhaden et al., 2011), with impacts of teleconnected patterns (Graf and Zanchettin, 2012). Furthermore, during periods of varying boundary conditions, such as the mid-Holocene it is likely that while ENSO remained active, there was an important change in the spatial pattern of the sea surface temperature anomalies (Karamperidou and Di Nezio, 2015). This change in the spatial structure of ENSO was not explicitly explored here, though explicit analysis of NINO3 and NINO4 (see Supplementary Fig. 1) may be insightful about changes in the ENSO system and its teleconnections through time. In addition, various studies have linked remote proxy variability to the tropical Pacific (e.g., Li et al., 2013) and hence it would useful in the future to investigate regions remote from the Pacific basin, such as in North America or China. Regardless of the spatial dynamics of surface temperature anomalies in the NINO3.4 region, we do not expect that the recommendation of considering proxy information from multiple is dependent on the NINO3.4 metric used to define ENSO utilised here.

We have also identified decadal- to centennial-scale modulation of ENSO behaviour, which has been highlighted previously (e.g., Karnauskas et al., 2012; Borlace et al., 2013). As such, a range of ENSO variability may exist during the Last Millennium that is not fully revealed by the comparatively short instrumental climate record. The existence of varying ENSO characteristics throughout the Last Millennium is also supported by proxy-based climate reconstructions (Cobb et al., 2003), which show variable ENSO characteristics include changing frequency and amplitude compared to modern during

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the Last Millennium. In ENSO-sensitive regions, temporally limited proxy-based ENSO reconstructions, such as from corals, may provide only a snapshot of ENSO history that cannot be extrapolated through time. The decadal- to centennial-scale modulations of ENSO may plausibly result from internal variability and/or external forcings, such as volcanic eruptions. We find multi-decadal to centennial- scale El Niño- and La Niña-like phases in CMIP5 piControl simulations (with no imposed external forcings). These are qualitatively similar to those shown in the externally forced Last Millennium experiment, suggesting that multi-decadal ENSO modulation can be stochastic. While Li et al. (2013), for example, agree that substantial stochastic ENSO modulation on these timescales can occur, model-based studies indicate that CMIP5 simulations of the Last Millennium demonstrate a more energetic and variable ENSO system on centennial timescales than in control runs (Ault et al., 2013). In Ault et al.'s study, control simulations did not agree with a suite of recent reconstructions while forced simulations are compatible, while Last Millennium simulations demonstrate ENSO variability closer to reconstructions. Overall, Ault et al. (2013) suggest that ENSO variability in models results from a thermodynamic response to reconstructed solar and volcanic activity.

On seasonal to annual timescales, previous model evidence suggests the radiative forcing due to volcanic stratospheric aerosols induces a La Niña episode that is followed by an El Niño episode after the peak of the forcing (McGregor and Timmermann, 2011). The association of eruptions and subsequent El Niño episodes has been demonstrated for forcings larger than that observed during the historical period for Mt Pinatubo (Emile-Geay et al., 2008). For large volcanic eruptions, El Niño-like conditions are favoured, with both the likelihood and amplitude of an El Niño episode subsequently enhanced (Timmreck, 2012). Furthermore, proxy reconstructions derived from tree rings across the Pacific reveal similar ENSO responses to those simulated, with anomalous cooling reconstructed in the east-central tropical Pacific in the year of volcanic eruption, followed by anomalous warming occurring one year after (Li et al., 2013). In this study, we also suggest that large tropical volcanic eruptions occurring between 1250 and 1600 CE (Supplementary Fig. 7), may produce decadal- to centennial-scale ENSO responses. We find, for example, that West Pacific El Niño- and La Niña-associated temperatures differ in character through the Last Millennium and with the historical 100-year epoch for the multi-model mean. The largest changes in this relationship occur in epochs coinciding with the timing of major volcanic eruption (e.g., 1258, Samalas, 1458 Kuwae) (Fig. 7), suggesting an extended influence of short-term volcanic forcings. Differences in ENSO-local climate relationships in these epochs indicates a notable ENSO response to large volcanic eruptions and suggests that short proxy records spanning periods of significant volcanic activity may be recording temporally-specific influences.

Overall we suggest that 1) changes in ENSO do not necessarily scale linearly to local scale impacts, 2) that there is likely a sensitivity of ENSO to the background climate state and 3) the decadal- to centennial-scale modulation of ENSO behaviour may arise from internal variability and/or external forcings such as volcanic eruptions. However, we considered only a subset of CMIP5 models that contributed palaeo-simulations and these contain systematic biases in ENSO representations (Power et al., 2013). In their study focused on understanding ENSO responses to volcanic forcings, Emile-Geay et al. (2008) suggested further forcing/response insights could be provided by GCMs with

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realistic ENSO cycles and asked whether the current generation of models were up to the task. Deficiencies in our theoretical knowledge of ENSO and the difficulties in representing physically realistic ENSO cycles in GCMs (Guilyardi et al., 2012) are a limit on providing robust quantitative understanding of forced and unforced changes in the ENSO system. Existing model simulations are useful for examining palaeoclimates, despite their biases and reveal spatially and temporally complex changes in ENSO and its teleconnected patterns under differing boundary conditions that should be considered when developing robust proxy interpretations and ENSO histories in order that these are most useful for constraining future ENSO behaviour under greenhouse forcings.

The palaeo-modelling type approaches utilised here do not attempt to replace proxy reconstructions, but rather demonstrate that combining multiple approaches can provide enhanced interpretations of reconstruction of past climate guiding our understanding of the most consistent physical explanations for change (Schmidt, 2010). This study highlights several avenues for further model-based research on ENSO variability and teleconnections:

- Several models have known difficulties simulating aspects of ENSO, such as the nonlinear response of rainfall to extreme El Niño episodes (e.g., Cai et al., 2014). Additional targeted experiments within a single climate model would provide further insight into the apparent complexity of ENSO impacts through time.
- Our present study did not comprehensively investigate the relative influences on various external forcings (solar and volcanics) and internal variability on ENSO characteristic, which would provide useful information for comparison with proxy records. These mechanisms could be investigated, for example, using a suite of simulations with single or varying forcings, which may provide valuable general insight into ENSO response to external forcings, including increased anthropogenic radiative forcings.
- More direct comparisons between model output and proxy reconstructions can be provided by employing pseudo-proxy techniques. Using this approach, a simulated time series intended to mimic actual proxy records ('pseudo-proxy') is generated from a climate model simulation (Anchukaitis and Tierney, 2012). The pseudo-proxy approach can be used to interrogate the necessary proxy density required for producing skilful regional climate field reconstructions and provide guidance on interpretations of reconstructions from particular locations (Smerdon, 2011; Wahl et al., 2014).

Acknowledgements

This research was supported by Australian Research Council Centre of Excellence for Climate System Science (grant CE110001028). We thank NASA GISS for institutional support; resources supporting this work were provided by the NASA High-End Computing (HEC) Program through the NASA Center for Climate Simulation (NCCS) at Goddard Space Flight Center. We thank NOAA for the C2D2 grant NA10OAR4310126 that supported the GISS-E2 last millennium simulations and

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thank all the groups that contributed to the CMIP archive. We acknowledge the WCRP's Working Group on Coupled Modelling, which is responsible for CMIP. The U.S. Department of Energy's PCMDI provides CMIP5 coordinating support.

Figure Captions

Figure Captions

Figure 1 Composited anomaly maps for surface temperature (K) for CMIP5 models (left, El Niño episodes; right, La Niña episodes) for historical experiment, showing multi-model mean (MMM) and each model. Rectangular boxes indicate the West, Central and east Pacific regions.

Figure 2 As for Figure 1, but showing composites from Last Millennium experiment.

Figure 3 Comparison of leading patterns (standardised, first EOFs) of monthly variability in surface temperature and precipitation for 20CR reanalysis (left: a, surface temperature; b, precipitation), CMIP5 models (b, surface temperature; d, precipitation). CMIP5 historical patterns are the multi-model mean (MMM) of the first EOF of each individual model for model years 1976-2005. Spatial correlation coefficients between NINO3.4 index and 20CR precipitation (e) and the CMIP5 MMM (f). Stippling indicates Spearman's rank correlations significant at the 95% level. Rectangular boxes indicate the East, Central and West Pacific regions. Only model years 1976-2005 are used for comparison as the historical experiment necessarily produces a non-stationary climate due to the time-evolving anthropogenic greenhouse gas forcings imposed.

Figure 4 Global mean NINO3.4 power spectrum (K^2/unit frequency, black) of Last Millennium simulations, relative to the red-noise (AR(1)) benchmark (dashed), for the multi-model mean (MMM) and each model analysed. The historical simulation is shown in black and the 5th-95th percentile range across the Last Millennium shown by purple envelope, calculated using 100-year epochs. Spectral power was calculated using a Morlet wavelet of degree 6.

Figure 5 Running annual-mean surface temperature anomalies (K) over the NINO3.4 region (5°N - 5°S, 170° - 120°W) for Last Millennium simulation for each model. Red/blue shading highlights departures from each model's long-term mean. Running means were calculated using a 240-month triangle smoother.

Figure 6 Running annual-mean surface temperature anomalies (K) over the NINO3.4 region (5°N - 5°S, 170° - 120°W) for extended piControl simulations conducted with GISS-E2-R (a) and IPSL-CM5A-LR (c) models. Red/blue shading highlights departures from each model's long-term mean. Running means were calculated using a 240-month triangle smoother. Control simulations are spun up to quasi-equilibrium and run for ideally >500 years, providing an arbitrary timeseries of model internal variability. Global mean NINO3.4 power spectrum (K^2/unit frequency, black), relative to the red-noise (AR(1)) benchmark (dashed) for GISS-E2-R (b) and IPSL-CM5A-LR (d) models.

Figure 7 Area-mean correlation coefficients (R) of NINO3.4 and local surface air temperature for the East (black square), Central (red cross) and West (blue cross) for the MMM and each model. Data points show correlation coefficients calculated for ten 100-year epochs comprising the Last Millennium simulation and for the historical simulation (1906-2005). Plot markers in grey indicate correlations that are not statistically significant (at the 5% significance level).

Figure 8 As for Figure 7 but showing correlation coefficients (R) of NINO3.4 and local precipitation.

Table Caption

Table 1. Details of CMIP5 experiments and models analysed. Further details can be found through the Program for Climate Model Diagnosis and Intercomparison (PCMDI).

Supplementary Figure Captions

Supplementary Figure 1 Location of NINO3, NINO3.4 and NINO4 index regions.

Supplementary Figure 2 Composited anomaly maps for surface temperature (K) for CMIP5 models for El Niño episodes for historical experiment (left) and past1000 experiment (right), showing multi-model mean (MMM). El Niño events are defined using the NINO3.4 (upper), NINO3 (middle) and NINO4 (lower) indices. Rectangular boxes indicate the West, Central and east Pacific regions. Plots indicate that teleconnected patterns may differ with ENSO index considered.

Supplementary Figure 3 As for Supplementary Figure 2 but showing composited La Niña episodes.

Supplementary Figure 4 Running annual-mean surface temperature anomalies (K) over the NINO3.4 region (5°N - 5°S, 170° - 120°W) for Last Millennium simulations conducted with MIROC-ESM and bcc-csm1-1 models. Red/blue shading highlights departures from each model's long-term mean. Running means were calculated using a 240-month triangle smoother.

Supplementary Figure 5 Comparison of leading patterns (standardised, first EOFs) of monthly variability in surface temperature for CMIP5 multi-model mean (MMM) for (a) historical and (b) Last Millennium experiments. The location of the NINO3.4 region (5°N - 5°S, 170° - 120°W) is indicated by a rectangular box.

Supplementary Figure 6 Composited anomaly maps for surface temperature (K) for CMIP5 models (left, El Niño episodes; right, La Niña episodes) for midHolocene experiment, showing multi-model mean (MMM) and each model. Rectangular boxes indicate the West, Central and east Pacific regions.

Supplementary Figure 7 Evolution of prescribed volcanic forcings for CMIP5 Last Millennium experiment, showing the two alternative data sets used by modelling groups, including (a) timeseries of stratospheric aerosol optical depth (AOD) at 0.55µm provided by Crowley et al. (2008) and (b) global hemisphere total stratospheric injections (Tg) from Gao et al. (2008). Large volcanic eruptions occurring between 1200 and 1500 are evident in both data sets.

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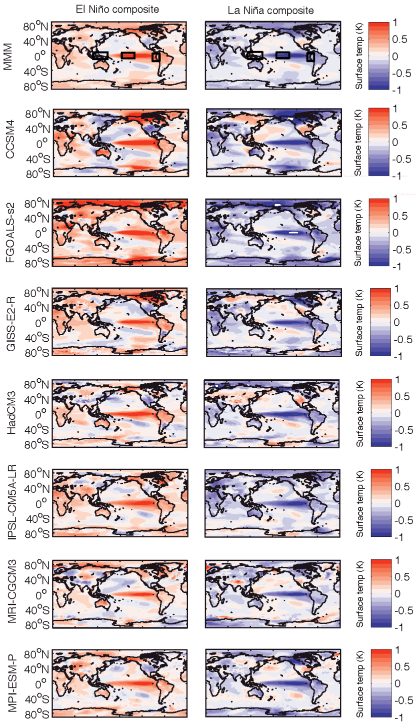
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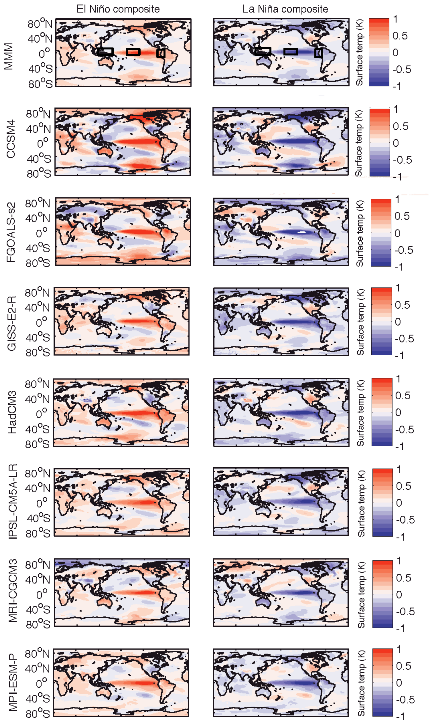
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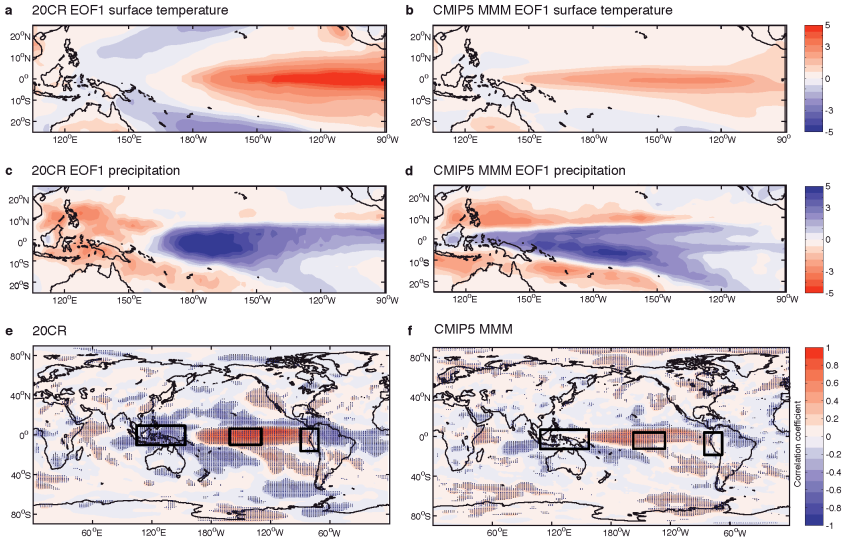
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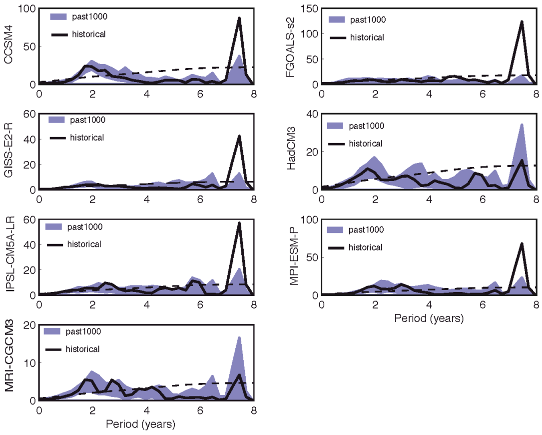
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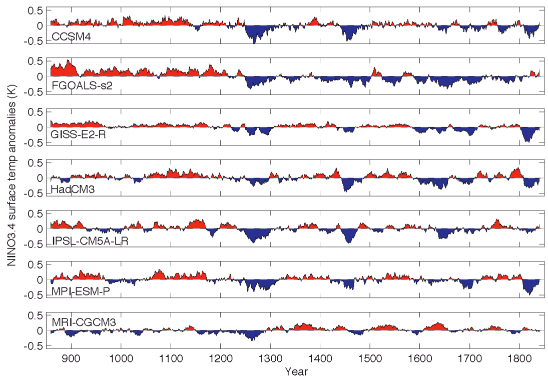
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1200
1300
1400
1500
1600
1700
1800
Year

Figure 6

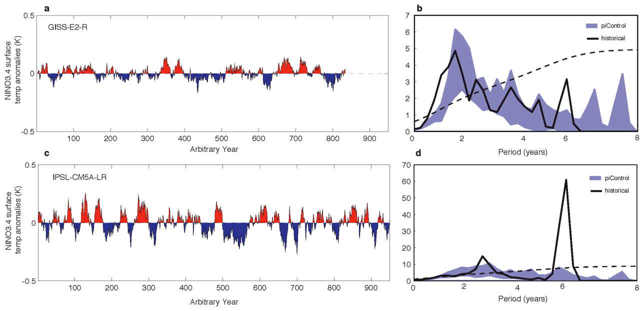
a
GISS-E2-R
NINO3.4 surface temp anomalies (K)
0.5
0
-0.5
100
200
300
400
500
600
700
800
900
Arbitrary Year
b
piControl
historical
7
6
5
4
3
2
1
0
0
2
4
6
8
Period (years)
c
IPSL-CM5A-LR
NINO3.4 surface temp anomalies (K)
0.5
0
-0.5
100
200
300
400
500
600
700
800
900
Arbitrary Year
d
piControl
historical
70
60
50
40
30
20
10
0
0
2
4
6
8
Period (years)

Figure 7

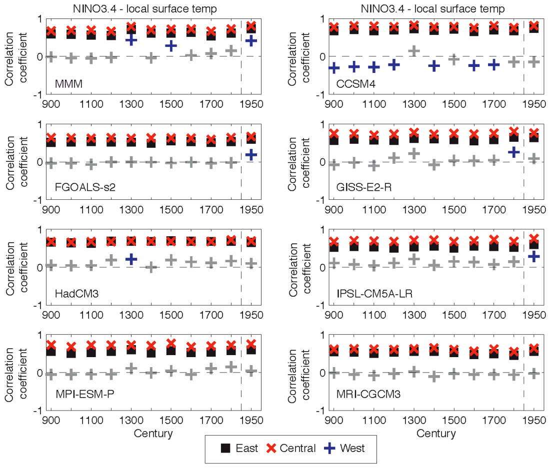
NINO3.4 - local surface temp
NINO3.4 - local surface temp
Correlation coefficient
1
0
-1
900 1100 1300 1500 1700 1950
Century
MMM
CCSM4
FGOALS-s2
GISS-E2-R
HadCM3
IPSL-CM5A-LR
MPI-ESM-P
MRI-CGCM3
■ East ✕ Central ✚ West

Figure 8

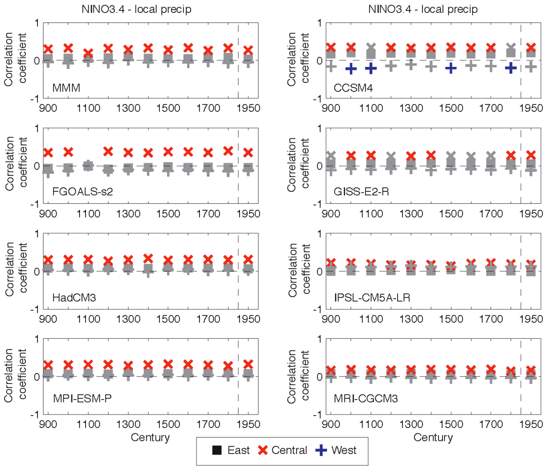
NINO3.4 - local precip
NINO3.4 - local precip
Correlation coefficient
1
0
-1
MMM
CCSM4
FGOALS-s2
GISS-E2-R
HadCM3
IPSL-CM5A-LR
MPI-ESM-P
MRI-CGCM3
900
1100
1300
1500
1700
1950
Century
■ East ✕ Central ✚ West

Table 1. Details of CMIP5 experiments and models analysed. Further details can be found through the Program for Climate Model Diagnosis and Intercomparison (PCMDI).

Experiment	Major forcings	Years Analysed	Models
historical	Time-evolving anthropogenic (greenhouse gases, aerosols, ozone) and natural (solar, volcanics)	1906-2005 CE	CCSM4, FGOALS-s2, GISS-E2-R,HadCM3,IPSL-CM5A-LR, MPI-ESM-P,MRI-CGCM3
past1000	Time-evolving greenhouse gases, solar, volcanics, land use and orbital parameters	850-1849 CE	CCSM4, FGOALS-s2, GISS-E2-R,HadCM3,IPSL-CM5A-LR, MPI-ESM-P,MRI-CGCM3
piControl	Non-evolving pre-industrial forcings	All	GISS-E2-R,IPSL-CM5A-LR

Sophie Lewis 28/7/2015 11:31 AM
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