Interactive comment on "Inferred changes in El Niño-Southern Oscillation variance over the past six centuries" by S. McGregor et al.

Anonymous Referee #2
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Reconstructing the long term variability of ENSO is important for understanding present-day ENSO dynamics, and combining proxy climate records is an excellent way to extract and enhance the common long term ENSO signal. Extracting common ENSO signals is challenging however, because the proxies often record different ENSO-related parameters, can be from regions teleconnected to the ENSO centre-of-action and therefore may only record a partial ENSO signal, and/or may be discontinuous or include dating errors. This manuscript present a new and simple method for combining proxy climate records to extract that common ENSO variance signal. Applying this technique to proxy records that span some or all of the past few centuries suggests that the interval from 1979-2009 displays largest ENSO variance.

I am supportive of this manuscript being published in Climate of the Past and feel that there are two main points that need to be addressed before this can be achieved:

We thank reviewer 2 for their effort evaluating our manuscript and the constructive comments. We have made substantial revisions to the manuscript in response to these comments, please see the revised manuscript and the individual responses below.

1) The main ENSO reconstruction using the MRV technique should be based on the single site proxy data.

Please see response to detailed comments below.

2) Wording in the figure captions needs to be improved, consistent terminology is needed between the main text and the captions, and some parts of the text must be clarified.

Please see response to detailed comments below.

I have expanded on these points below in an effort to assist the authors in revising the manuscript.

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1) The main ENSO reconstruction using the MRV technique should be carried out on the single site proxy data.

The authors argue that the lack of independence of the multi-proxy reconstructions may enhance the noise component distort the common ENSO signal. This is a valid point but my concern is actually the opposite. That by using the same proxy record in multi-proxy reconstructions, and then combining the

multi-proxy reconstructions, (and including some of the original proxy records again), the ENSO signal may be artificially enhanced. The multi-proxy reconstructions have already in some way filtered the ENSO signal from the noise and this already-filtered signal is combined (by the new MRV method) with other already-filtered signals (from other multi-proxy reconstructions) to get a common signal that has a potentially stronger ENSO.

After discussing the independence of the various multi-proxy synthesis products, the authors then go on to make an MRV reconstruction based on independent data (i.e. using individual proxy records only (no synthesis products)).

Why not simply present that single site-based ENSO reconstruction and leave it at that. I feel that this would be a far better estimate of our state of knowledge of ENSO for the past 600 years, even if it does contain ENSO variance data that appears anomalous compared to the common reconstruction (e.g. some of the pink dots in Figure 9a and c). I strongly recommend the authors present their single site reconstruction as their main ENSO synthesis product. Looking at Figure 9 I don't think it will change their overall conclusion but it will give us confidence because it is based on truly independent data.

One of the main goals of this manuscript is to synthesize existing ENSO reconstructions to arrive at a better estimate of past ENSO variance changes, rather than simply identifying another new estimate not placed in the context of those already presented in the literature. As such, we choose to retain all analyses presented in the paper as we feel that each adds value to the manuscript as well as showing robustness across the different source data types. We have however altered the text in the abstract, discussion and conclusions sections to highlight the fact that our results appear to be consistent regardless of the choice of source proxies utilized in the analysis.

Also on Figure 9, which are the records that appear anomalous (i.e. above the red line in Figure 9)? I feel the authors need add some discussion of these specific records and why they might be different.

It is outside the scope and goals of this study to detail the outliers here. Indeed, all of the model analysis prior to this section suggests that information gathered from a common signal gathered from numerous locations provides a better estimate of ENSO's past variance changes than those obtained from single stations. Thus, we choose to retain the focus on the various MRV signals presented.

Why the East African lake varves not included in the single site-based reconstruction?

This proxy was utilized in Section 4 of the manuscript. In section 5 of this analysis, as stated on lines 30-32 of page 11 in the revised manuscript, we focus on single stations proxies from regions within/surrounding the Pacific Basin.

2) Wording in the figure captions needs to be improved, consistent terminology is needed between the main text and the captions, and some parts of the text clarified. This may seem a trivial point but at present it is very difficult to follow what was presented in the figures and improving this will allow better understanding of the research and others to adapt the technique for different proxy climate syntheses. Wording between the figure captions and text is often inconsistent making parts of the manuscript very difficult to understand, at least for me. I have listed the parts I found most confusing below, and made suggestions as to how to improve the wording. Note: also included in the points below are additional comments and recommendations.

We thank the reviewer for this comment. In an effort to improve the readability of the manuscript we have now reworded the manuscript text in various places as suggested (see responses below) as well as the figure captions to ensure consistency.

Abstract:
"These paleo-proxy reconstructions have typically attempted to reconstruct the full tem- poral variability of ENSO, rather than focusing simply on its variance." What does "full temporal variability of ENSO" mean in this context? Aren't the records proxies for a given climate parameter where that parameter varies on annual, interannual, decadal etc. scales, and isn't ENSO by default the interannual band, so what do you mean by the "full temporal variability of ENSO"? This for me doesn't mesh with "focusing sim- ply on its[ENSOs] variance" – ENSO variance being the interannual band can itself be modulated on multidecadal scales. May you please define these terms.

We have now reworded this sentence to make it clear how the current work is distinct from previous ENSO reconstructions. Basically, previous reconstructions have attempted to reconstruct the temporal variability of ENSO, and then they proceed to calculate its running variance almost as an afterthought. Here, we focus simply on trying to reconstruct ENSO variance, with no consideration given to its temporal variability (i.e., when individual ENSO events occurred). See lines 20-21 of page 1 of the revised manuscript.

"Here a new approach is developed that synthesizes the information on common low frequency variance changes from various proxy datasets to obtain estimates of ENSO variance" Synthesising variance to estimate variance is confusing. Do you mean ex- tract the ENSO variance from individual records and then combine those to extract the common ENSO variance? May you please clarify.

We synthesize variance information from numerous proxy sources to provide a unified estimate of the variance. This sentence has now been clarified in the revised manuscript, see lines 21-23 of page 1.

"we find that the common ENSO variance over the period 1600–1900 was considerably lower than during 1979–2009" This sounds like a 300-year period is being compared to a 30-year period, which is a bit of an unfair test for the 1979-2009 period. Rather, do you mean that ENSO variance for 1979-2009 is

higher than the common ENSO variance for any 30-year period during the interval 1600-1900? Please clarify.

Yes this is what is meant. We have now altered the abstract to reflect this suggested change. Please see lines 3-6 of page 2 of the revised manuscript.

Introduction:
"i.e., that a good temporal correspondence between a given climate variable and ENSO translates also into a high correlation between multi-decadal variance changes in this variable and in ENSO." Is it possible to give a specific example?

Many studies that present new ENSO reconstructions firstly discuss the correspondence between their proxy and the observations (e.g., Niño 3.4 region SSTA). Most then proceed to analyze the running variance of the newly defined proxy, discussing how these past variance changes relate to current ENSO variability. Examples of this can be found in McGregor et al. (2010), Wilson et al. (2010) and Li et al. (2011, 2013), among others, thus implicitly making the assumption that because the proxy is correlated with observed ENSO, the running variance of the proxy would also match that of ENSO. We now cite several of these examples in the revised manuscript when discussing this implicit assumption (see line 8 of the page 3 in the revised manuscript).

Methods:
". . .whether a good temporal correspondence between a given regional climate variable and ENSO can be used to imply that the variable will also provide a good represen- tation of ENSO variance." May you give a specific example of where this is and isn't the case – this will help in understanding the subtle difference between a variable's correspondence with ENSO and its ability to capture ENSO variance.

This is what is presented in Section 3.1, see the newly added text on lines 9-14 of page 5. Outside of this manuscript we have not come across this being discussed in the literature previously. However, one of our co-authors presented a poster on this subject in CM2.1 last year, see:
http://www.gfdl.noaa.gov/~atw/yr/2013/wittenberg_20130207.pdf

Why was surface air temperature selected and not sea surface temperature (SST)? These parameters are strongly correlated in the tropics, granted, but the coral proxies are at least partially SST. Perhaps you could add a couple of sentences explaining?

Surface temperature is defined in both models as the topmost ice/land/ocean model level temperature. So, over ocean T_S is equal to SST.

"Two maps" and "two spatial maps" are confusing as you could be comparing contours and colours, or 2a, 2b, 2c, and/or 2d maps.

We have now clarified this in the text, see lines 1-5 of page 5 in the revised manuscript.

"Carrying out the same analysis for CM2.1 and CCSM4 precipitation data reveals some interesting differences between the running variance (precipitation running variance – ENSO running variance) correlation patterns and the raw (precipitation – ENSO) cor- relation patterns in the tropical Pacific (Fig. 2b and d)." Which figure part is which? The use of "-" (e.g. precipitation running variance – ENSO running variance) makes it seem like you are subtracting these parameters but that's not actually what's been done. Also, the syntax is ambiguous – you could be comparing CM2.1 vs CCSM4, or comparing the individual parts of the figure, whereas you are actually comparing the correlation patterns.

We have now altered the text to be easier to read and to remove any ambiguity. See lines 6-18 on page 5 of the revised manuscript.

This is also an example of what I described for the figure caption where the terminology is different from the caption making it hard to understand. Please reword for clarity.

We have now updated the caption of Figure 2 to be consistent with the manuscript text.

"These differences between the correlation maps are reflected by the spatial correlations (r) of 0.67 (r2 = 0.45) and 0.55 (r2 = 0.31) respectively." Again ambiguous. Are the spatial correlations for the information on the maps or between the maps? And which r (r2) values corresponds to what?

We have now altered the text to be easier to read and interpret. See lines 15-18 on page 5 of the revised manuscript.

"...variance of ENSO binned according to the correlation between precipitation and ENSO." This phrase made no sense to me until I looked at the figure. Is it possible to clarify? "For instance, in CM2.1 if a precipitation signal is selected that has an r2 value of between 0.6 and 0.7 when compared with the time series of ENSO SSTAs, there is a 10% chance that the running variance of that precipitation time series will have no significant correlation ($r < 0.31$ or $r2 < 0.1$) with the running variance of ENSO (Fig. 3a). This indicates that ENSO may influence the sign and timing of the rainfall change at this location, however unrelated processes influence the magnitude of that change." This is a very interesting point however it took multiple reads and flipping between the text and figure before I got what was going on. I think the issue is the phrasing of "10% chance" – could the terminology simply be changed to have the same values as the y-axis?

We have now rephrased this sentence so it is better placed in the context of Figure 3. See lines 26-29 of page 5 in the revised manuscript.

"running variance of the median (common) precipitation data" Again different from the figure – could you put in brackets "50% quantile" to make it easier to identify what you are referring too?

How we calculate the common signal is now explained in more detail (see lines 1-4 of page 6 in the revised manuscript), however, we still refer to the median rather than the 50th percentile, as this is the definition of the median.

"For instance, if we pick two geographic locations for which the median (common) precipitation signal has an r2 of between 0.6 and 0.7 with ENSO, there is only a 1% chance that that the running variance of that common precipitation time series will have no significant correlation ($r < 0.31$ or $r2 < 0.1$) with the running variance of ENSO. This is 10 times less likely than the case with precipitation data only sourced from one location. This result is consistent with CCSM4 data which suggests a common precipitation signal, from two geographic locations that have r2 of> 0.7 when compared to ENSO SSTA, will make it 3.5 times less likely that the running variance of that signal will have no significant correlation ($r < 0.3$ or $r2 < 0.1$) with the running variance of ENSO (Fig. 3b)." I'm afraid I was confused here too: 1% chance, 10 times less likely, r/r2 values, and then r2 on the figure 3 y-axis – I can't keep track of what's being compared with what. Perhaps start by stating the figure 3 y-axis values for the things you are comparing and then move on to state the % chances and likelihoods?

We have now tweaked the text to improve consistency with the Figure 3 caption and axis labels.

Page 2935 final paragraph. This is a nice summary of the model results. Why not test other parameters ENSO-relevant commonly reconstructed by climate proxies?

Thank you. This suggested further analysis is beyond the scope of the current work but may be explored in the future.

Figure 2 caption:
This figure caption took several reads and a lot of back and forth to the text for me to understand what I was seeing, when once I got it I realised the concept was really quite straightforward. I think this caption (and all captions, actually) could be improved with: a) A title sentence stating what the figure is about b) Some clearer definitions that are consistent between the captions and the text.

For example, define the HPF annual mean (July-June) anomalies as something along the lines of "simulated raw" Ts/precip. Then the contours become the correlation between "simulated raw" data and annual mean N34 SSTA. Colours become the correlation of 30 yr running variance of the simulated raw data with the 30 yr running variance of annual mean N34 SSTA. Note for the contours it is written as "annual mean N34 SSTA", whereas for colours it is "HPF annual mean N34 SSTA". This chopping and changing occurs for several parameters and add to the difficulty in understanding the caption (and related text). c) Then add a sentence somewhere explaining what the figure means e.g. That for Ts raw data

and 30 yr running variance show similar correlation patterns with annual mean N34 SSTA, whereas these correlation patterns for rainfall often differ.

Figure 2 part labels – there are two "c)"s.

Thank you, we have now changed the figure label, updated the figure caption and the text to better describe the analysis and what is plotted.

Figure 3 caption:
"The inset histogram displays the distribution of squared correlation coefficients calculated between precipitation running variance and the running variance of ENSO from the identified x-axis (grey shading) bin." I read this numerous times and I just couldn't figure out what had been plotted. Also, what are the black and blue lines in the normalised counts plots? I'm sorry I can't make any suggestions as to how to reword but I really didn't get this.

We have now reworded this sentence of the caption to better describe what was plotted.

I struggled to distinguish the "+" symbols from the "x" symbols in the figure. Perhaps try circles and triangles?

We have now replaced these symbols of Figure 4 and Figure 6 with triangles and squares to make them easier to distinguish.

Section 3.2.1:
Opening paragraph. This could be made clearer by adding a plain-english sentence describing MRV and RVM (perhaps this needs to come earlier in the paper). E.g MRV = calculate the running variance for the interannual band for each individual proxy and then calculate the median of all of those. RVM = combine the individual proxies first and then extract the interannual band and calculate the running variance.

We have now added a more descriptive sentence describing the MRV and the RVM as suggested. See lines 11-14 of page 7 in the revised manuscript. We now also repeat this description on lines 10-14 of page 8, and lines 11-12 of page 9.

I note there's no callout to Figure 5b and d.

We have now added a call out to panels b and d of Figure 5 (see lines 1-4 of page 9).

Section 3.2.2:
"What varies between these four sets, however, is the ratio of the time series that is subject to the introduced temporal shift, changing from 1/5, 1/4, 1/3, and 1/2." Do you mean then that one fifth (or one quarter etc.) of the records are shifted randomly by between 1-5 years? Could you add a follow up sentence to clarify what you mean?

Done, please see lines 22-24 of page 8.

Figure 7 caption:
Include a reference to table 4. Also, there's another new term in the caption "observed ensemble median running variance" – please relate this to table 1 and the wording in the text.

Done, please see the revised Figure 7 caption.

Figure 9 caption:
What is the difference between the "ensemble median running variance" and the "ob- served ensemble median running variance"? I presume these are the same thing? Also in (b) and (c) which "median" are referred to here? All proxies median, tree-only or coral-only proxies median, median from Table 1 reconstructions? May you please clarify.

This has now been clarified. Please see the revised Figure 9 caption.

Section 5:
Some figure caption callouts appear to be incorrect e.g. Fig. 8a insert but I can't see an insert for figure 8. Please check all the callouts in this section.

Thank you, we have now fixed all call outs.

In all the relevant figure captions please use more useful terminology than 'proxy 1' etc. It was quite frustrating to be continually flipping between the figures and the table to work out what which record was which.

We have now altered the reconstructions labels in the legends of Figs. 1 and 8, and Tables 1 and 2 to provide a more intuitive reconstruction title.

Finally, may the authors please add some more explanation as to why the MRV method works better than the RVM method.

We have now discussed this on lines 2-7 of page 7, lines 14-17 of page 8, and lines 14-17 of page 14 in the revised manuscript.

Expand the discussion on limitations and possible caveats on applying the technique.

For example, can the technique be applied to discontinuous records?
For example can the technique be used with the types of data that come from fossil coral boulders (e.g. Cobb et al 2003, 2013)?
What are the advantages and disadvantages of this technique compared to the other synthesis techniques listed on page 2940?

The results of our study suggest that working with running variance time series is preferable to working with the raw time series, if the goal is to reconstruct running variance time series. We have now tried to clarify what was meant by

this on line 2-4 of page 7, lines 14-17 of page 7, and lines 13-17 of page 14 in the revised manuscript.

However, our method of simply identifying the common signal as the median of the source proxies is not sensitive to missing data, like a PCA analysis; as such it can be used with discontinuous data. We now discuss the potential advantages of this technique in the 3rd paragraph of Section 6 in the revised manuscript.

Summary and conclusions:
The authors discuss limitations of their technique and study, and implications for ENSO reconstructions – I feel this should be part of the discussion section, since they are important new points rather than summaries or conclusions.

We have now retitled the 'summary and conclusions' section to 'discussion and conclusions' to better fit its content.

Possible record to include in the single site synthesis:
Kelly A. Hereid, Terrence M. Quinn, Frederick W. Taylor, Chuan-Chou Shen, R. Lawrence Edwards and Hai Cheng. Coral record of reduced El Niño activity in the early 15th to middle 17th centuries. Geology 2013;41;51-54 doi: 10.1130/G33510.1

It is not possible to include this proxy in our single site synthesis at this late stage, however, we do cite this manuscript in Section 6 of the revised manuscript.