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## Reply on RC3

Lina Boljka et al.

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Author comment on "Revisiting conceptual oscillator models for the quasi-periodic component of the El Niño Southern Oscillation" by Lina Boljka et al., Weather Clim. Dynam. Discuss., <https://doi.org/10.5194/wcd-2022-51-AC5>, 2023

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We thank the reviewer for careful consideration of our manuscript and their constructive comments that have helped improve the original manuscript. Note that line numbers below in our responses refer to the revised manuscript.

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### major points

*(1) The new method: The authors do try to explain the method, but unfortunately it fails to be clear enough. This would need to be improved. It would help greatly if the authors could more clearly explain what the elements of an MEMD mode are. Ideally in reference to something that most readers know (e.g. EOF-modes). An EOF-mode, for instance, has an eigenvector (pattern), eigenvalue (amplitude) and principle component (time series), they are ordered by explained variance, and are orthogonal to each other both in terms of eigenvectors and PCs. What are the elements of an MEMD mode?*

The elements of an (M)EMD mode will ultimately depend on input data. In its most basic form, its elements (output data) would be timeseries for different timescales that can be identified within the data - so frequency/period/timescale can be another element. Modes are ordered from highest frequency (shortest period) to lowest frequency (longest period) and trend (the last mode is considered a trend of input timeseries). See l. 153-155, 229-230, 726-727, Appendix A, Figs. S7-S11 as examples for this from ENSO data, and Section S.3 for a simple example (as suggested by the reviewer in the comment below).

If spatio-temporal data are used, we first reduce their dimensionality via EOF/PC analysis (like in this study). Then, the input data for MEMD are, e.g., 20 PCs (each PC has an EOF pattern associated with them). The output from MEMD analysis are timeseries (IMFs) of these PCs, where each PC is split into a certain number of IMFs (here we have 22) of which each IMF has a specific timescale associated with it (and is consistent across the 20 PCs). This is now shown in Table S2. For each IMF we can then take the 20 PCs and their EOFs and reconstruct spatial pattern evolution as described in Appendix A. Thus, we can also extract spatial evolution associated with each IMF (e.g., shown in Figs. 2, S2 for a composite over Nino3 index for IMF13,12, respectively), which is non-stationary (evolves with time; i.e., it is not just one constant/stationary pattern like in EOF analysis).

As mentioned above we have now provided additional text, plots and tables (as also

requested by other reviewers) to help the readers understand MEMD better. For further visualisation of the (simpler) 1D method, the reviewer is referred to Wu and Huang (2004; doi: 10.1098/rspa.2003.1221) or this website: <https://towardsdatascience.com/decomposing-signal-using-empirical-mode-decomposition-algorithm-explanation-for-dummy-93a93304c541>.

*Overall it appears that the method is a fancy trick (that is hard to understand) to time filter the data. What is the value? What do we learn from this method that we did not already know?*

We believe that the main value of (M)EMD is that it can objectively identify intrinsic timescales within the timeseries (i.e., without predefining a range) and output timeseries for each timescale (IMFs) in a nonlinear and nonstationary way. It will also extract the co-varying part of the system, i.e. identify common timescales across different timeseries (see l. 147-157). In this study, we then use the output timeseries (IMFs) and their frequencies to extract periodic signals based on red-noise test (as described in Appendix B). This is a novel way for identifying periodic modes of variability using (M)EMD (hence the lengthy Appendix B), even though the red noise test is applied in a very similar manner as in a regular periodogram. Thus, we use MEMD to identify frequency range in which ENSO is quasi-periodic (roughly 2-4.5 years), without any predefined range (see l. 155-157) and with a method that is nonlinear/nonstationary (l. 147-149). Note that the frequency range is identified because of the non-stationarity of the method, i.e. timescale varies in time (see Fig. 1). With this method we are also able to identify regions of quasi-periodic variability (e.g., across the tropical Pacific in Fig. 2 – significant points, i.e., without grey shading). However, the main focus of this study are the ENSO oscillator models, for which we found some inconsistencies with the existing theories by filtering timeseries to the timescales that MEMD yielded (see section 3.2 in the manuscript). For example, IMF11 & IMF14 (still somewhat within ENSO timescale range of 2-8 years) exhibit very different dynamics from IMF12,13 (Fig. 4 vs. Fig. 3) and we only realised this once we plotted equivalent Figs. to Figs. 3,4 for different IMFs. Thus, the focus here is on oscillator models, and we keep most of the MEMD discussion in the Appendices/supplement (see also responses to comments below).

Note that we have successfully used this method (MEMD + red noise test as presented here) on other fields (not yet published) to identify regions that have potential quasi-periodic variability and have not been established before. Here, such a region is clearly identified across the tropical Pacific in Fig. 2 (as mentioned above) - though in this case the quasi-periodic region was known in advance. Thus, we believe there is value in using this method.

*Often it is easy to illustrate this with an idealised constructed example that has strong similarity to the real world, but at the same time can be controlled, so that the 'truth' is known.*

We have added an example with sine waves of different frequencies to show how the method works. Of course, in this case any linear/stationary method would be capable of identifying these simple modes - see Section S.3 in Supplement. This is merely to show that MEMD can extract correct waves (even if it is at times imperfect).

We also chose ENSO initially as a real-world example that is generally well-known. ENSO is a well studied phenomenon and thus a great starting point for understanding a new method that may be used for identifying quasi-periodic signals. However, we realised later that there were some inconsistencies with oscillator models, thus we focused on that here.

*(2) Red noise test: It is not clear how this is done. Fig. B1 shows one blue dot above the 95% line, but is unclear what this blue dot is and how this would relate to the two MEMD*

*modes IMF12 IMF13. How are the two modes selected and what does it have to do with Fig. B1?*

The procedure goes as follows: (1) input timeseries of interest (e.g., 20 PCs) into MEMD algorithm; (2) get, e.g., 22 IMFs for each PC as output from MEMD; (3) for each IMF reconstruct data (from 20 PCs and their EOFs) to yield spatial patterns of each IMF; (4) average data within, e.g., Nino3 box for each IMF to get Nino3 timeseries for each IMF (i.e., 22 timeseries of different timescales, 22 IMFs for Nino3); (5) compute average frequency/period as well as squared amplitude of each IMF; (6) get natural logarithm of both squared amplitude and period of each IMF; (7) plot  $\log(\text{period})$  vs.  $\log(\text{amplitude})$  of each IMF as scatter plot shown in Fig. B1d. So, in Fig. B1 each dot represents the mean amplitude and frequency of each IMF that we have identified within our timeseries. If we count dots from left to right we quickly realise that the 12th and 13th point (i.e., IMF12,13) are above red noise threshold (i.e., red dashed line) in Fig. B1d. Different panels are just for different timeseries/methods as described in caption (and text in Appendix B). We describe MEMD method in detail in Appendix A, i.e., points (1) to (4) above, whereas construction of red noise test and thus Fig. B1 is done (in detail) in Appendix B - see equations and their descriptions. We have added further clarifications on points (5)-(7) to l. 769-776.

The main idea for the red noise test comes from a "regular" periodogram. Since each IMF has an amplitude and frequency, we can imagine them as a periodogram, i.e., each IMF represents a different point on a periodogram. From that we can then use the "usual" red noise test (for periodograms - like in Fig. B3), which lets us find IMFs (blue dots) that are above red-noise threshold (above red/pink dotted line as stated in the Appendix's text - see l. 838-839). Please note that similar methods have been used in previous studies for EMD (as cited in Appendix B). Again, this is described in detail in Appendix B2 with equations. We also use the normal periodogram and its red noise test in Fig. B3 - merely to show that Fig. B1 yields IMFs with "correct" timescales as significant.

*(3) Data from 1870 for thermocline depth and winds: It seems unlikely that much is gained in this analysis by using data going back way before we have any confidence in the observed data. Why is this done? Why does this analysis require such a long period of time using probably very poor data?*

We do this mostly for consistency (and significance). When we constructed the prediction model we needed as much data as possible due to many lags used and the need for a "testing" and "training" set. Also, statistics are better. While not much is gained, also nothing is lost as the 19th century data does not really contaminate the timeseries analysis, but it can change the average timescale/amplitude of the timeseries (as its timescale/amplitude varies with time). This is not an issue as the modes that we find are consistent with modes identified in previous work using other methods and over shorter periods, e.g., 1970+ (as stated on l. 282-288). We initially also used OISST data (1980-present), and MEMD results were consistent with the presented results here (not shown).

We have added a few sentences addressing this on l. 111-114.

*(4) Section 3.2 "Conceptual oscillator models of ENSO": This section is largely unclear and much of it appears to be unrelated to the topic. This needs substantial rethinking. HOW does it relate to the MEMD?*

*I recommend to strongly reduce this section.*

The whole introduction/abstract/conclusions are focused on ENSO dynamics and ENSO's conceptual models. As this is the main focus of this study we have kept the sections the

same. However, to avoid confusion about the main topic, we have changed the title to "Revisiting conceptual oscillator models for the quasi-periodic component of the El Niño Southern Oscillation".

MEMD here is used as a way of identifying a range of frequencies that yield quasi-periodic behaviour within ENSO (Niño3 region), i.e., it is merely used as a tool (but a lot of description was needed as it is a relatively new method). After that, we re-evaluate oscillator models within this particular range of frequencies (see also response to major comment (6) below and responses to major comment (1) above). We considered reducing the MEMD section in Methods instead, but then the rest of the text would likely be harder to follow.

We have added/removed a few sentences throughout the manuscript to keep this thread - see, e.g., l. 9-14, 78, 93-94, 103, 145, 218, 259-260, 316-317, 352, 496-512, 551-554, 610. See also track changes.

*(5) Section 4.2 "Prediction": This section is hard to follow. It is not easy to understand what is predicted here. It seems to be a highly filter part of the NINO3 SST? Not clear what is learned from it. Highly filter SST is more predictable?*

One of the goals of detecting and understanding quasi-periodic variability is to identify the predictable components of the climate system and isolate them from the (red) noise. With the prediction presented in section 4.2 we demonstrate that tropical SSTs in the frequency-band we identified as quasi-periodic via MEMD (i.e., IMF13) is indeed predictable well in advance (as expected) – i.e., IMF13 is the predictable component of the tropical SSTs. However, a wider frequency-band (e.g., IMF12 + IMF13) is less predictable.

Note that the statistical model is constructed on raw data (not filtered data), filtering is only performed as post-processing to see if the quasi-periodic band yields better prediction skill.

We have further clarified this on l. 551-554. Also, we have added a schematic on how prediction model is constructed in Appendix C and moved most of the text describing it there as well - hopefully this helps clarify section 4.2.

*(6) last two sections: They seem to not clearly fit to the initial outline of this study, which is to introduce the new method. The connection is not that clear and it seem to drift into other aspects.*

We apologise for the confusion. The initial idea was to introduce MEMD, but we later realised that ENSO oscillators are very interesting. However, we only realised the issues with these oscillators when we plotted line composites (cf., Fig. 3) for different IMFs. Thus, the two fit well together. As mentioned above, we have changed the title and tried making it clearer in the text that the main aim here is to use MEMD to re-assess oscillator models of ENSO. We have added comments throughout the text - see answers to comments above and track changes.

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**Other points (in order as they appear in the text):**

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*line 101 "... ENSO teleconnections to the North Atlantic ...": The authors seem to indicate that they include SLP into the MEMD mode analysis to include teleconnections to the North Atlantic. This seems strange and is not further explored. It would also miss much more*

*obvious teleconnections to many other regions on the globe. I would suggest to delete any reference to the NAO.*

We agree with the reviewer and have removed such references except in conclusions (future work).

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*line 112 "This gives greater weight to SST data ...": Unclear! Later the authors state that the PC of the EOF-modes are used. So the data horizontal grid resolution should not matter. This needs clarification. Further, why would the SST be weighted higher? The later discussion focus on the ENSO dynamics including winds and thermocline. So, it should be equally weighted?*

The horizontal grid resolution does matter. If more points come from SSTs then SSTs dominate the PC/EOF decomposition. If SSTs are not weighted more, then we can pick up internal ocean or noisy atmospheric dynamics from the other 2 fields that can interfere with the signal. For example, the domain we use for the MEMD analysis spans 25S to 25N in latitude (not just 5S to 5N used for Nino3/4 definition) to capture the off-equatorial thermocline depth that matters for the West-Pacific oscillator model. However, 25S/25N are further away from the Equator (0N) and can thus be affected by extratropical variability (i.e., not just tropical) – especially in the wind stress component, which can then in turn affect the intrinsic timescales present in the input data of MEMD analysis. Similarly, if the other 2 fields (wind stress & thermocline depth) do not have the same quasi-periodic variability as the SSTs, but instead are just red-noise-like, it can jeopardise identification of quasi-periodic variability of SSTs (via MEMD) when the 3 fields are combined. Thus, we suggest careful consideration of input data for MEMD. See l. 119-125.

Also, since the focus here is understanding Nino3/ENSO dynamics, we “enslave” wind stress and thermocline to the SSTs to extract variability associated with quasi-periodic nature of Nino3 index, which defines ENSO in the first place. Oscillator models were developed in the past for a better understanding of ENSO’s quasi-periodic nature, which is primarily seen in the tropical SSTs. To remain consistent with previous work in trying to explain SSTs’ quasi-periodic variability, we thus give more weight to the SSTs in our analysis.

Ultimately, the timeseries we get from quasi-periodic IMFs (12,13) can be extracted from band-pass filtered data as well. Thus, the results we obtain via our MEMD analysis are still representative of the variability in that frequency band not just for SSTs (Fig. 1) but also for wind stress and thermocline depth (not shown; implied via Fig. 3b).

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*line 116 "... whereas MSLP (not shown) is computed in the North Atlantic sector (80°W - 30°E, 25°N - 70°N)": Unclear why this is included. It seems unrelated to this work. This should be removed.*

Yes, agreed.

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*line 135 "... methods methods ...": -> "... methods ..."*

Done - see l. 153.

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*lines 139-145; description of the EMD method: Can this be visualised? What does the time series of the first mode look like? A figure may help.*

*Does this define a mode order? The first mode is the highest frequency and the last the lowest?*

Yes it is exactly like this (see also above). See Figs. S7-S11 for IMF timeseries obtained via MEMD and Section S.3 for a simple example. Note that EMD is a well-established method and we just provided a quick recap. MEMD is much more complex and the reader is then referred to the relevant papers.

We have added additional descriptions/figure references, but slightly further down in the text - see l. 187-190, 229-230, Appendix A, and the answers to comments below/above.

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*lines 139 "(i) first we identify local minima and maxima of the timeseries ... "; description of the EMD method: I am already lost at step one. What time series? The data used are several fields, which have many time series. How does this work for MEMD modes?*

We first introduce the EMD method (1D version) as it is much simpler to understand (this may not have been clear initially, so we added a few words on l. 159-160); then we extend it to MEMD, which is much more complex. In (i) we thus refer to "input timeseries" (added; see l. 160). MEMD solves a problem on n-spheres and is thus much harder to visualise or explain in a few sentences (see Rehman and Mandic 2010 for details; stated on l. 174-178).

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*line 232 "IMF12 and IMF13": What does "12" and "13" mean? How have these two been selected? Is it a coincident that they follow in order?*

IMF12,13 are selected via a red noise test as described in Appendix B (Fig. B1). 12 and 13 mean 12th and 13th mode in terms of frequency ordering (see above as well).

It actually is a coincidence that we identify modes 12,13 - it could have been any other mode(s) as long as those modes are the ones that are quasi-periodic, which is a prerequisite for identification of significant modes in the present study. As mentioned above, we do not predefine a range in which periodic signals should occur.

Another prerequisite (sanity check) is for the modes to be well separated from other modes in terms of mean timescales (otherwise two modes may be "mixed" and thus not really separate). The latter is done somewhat subjectively based on Fig. B1 (e.g., Fig. B1c,d shows many dots at higher frequencies/lower periods that overlap or are very close to each other, but that is not the case around the significant modes, which are "well" separated). Note that the frequency ranges of different IMFs can be wide and overlap slightly on the tails of the "distribution" - see Fig. S1 for periodograms of IMFs12,13.

We have added additional notes along those lines on, e.g., l. 229-230, 244, 726-727, 852-860.

*The authors find two modes: Does this mean two independent modes?*

While EMD & MEMD are constructed so that modes would be largely independent, we can still find small correlations across different modes. This is due to non-stationarity of the method, which can result in limited covariability over limited time periods (Fig. 1 in the

main text – l. 291-296). Here, we find a correlation of about 0.27 between IMF12 and IMF13 (as stated on l. 293). We added an additional sentence on l. 157-158 as well.

*For instance, a periodogram may have 2-5 points in a series above the 95% confidence limit. Each point is an independent estimate of harmonic functions, but it does not mean that there are 2-5 "modes". So how should we interpret that there are two modes? Does it mean the time scales are broader?*

Each IMF mode is associated with a range of timescales as mentioned in the text (see l. 266-276), i.e., IMF12 has a range 17-32 months and IMF13 has a range 25-52.5 months. Their mean periods are 22 and 34 months, respectively. See also Fig. S1 for periodograms of IMFs12,13. The range of timescales of each mode stems from the non-stationarity of the method and can be nicely seen in Fig. 1, where in some decades the variability in IMF12,13 is slower than in other decades (see also text around Fig. 1).

However, IMFs are timeseries and a direct output from MEMD, thus they are identified as modes of variability from MEMD by definition, but (as mentioned above) they can represent a range of timescales. Periodogram is a different method, but can be used to identify specific frequencies where quasi-periodic behaviour exists, which then allows us to filter the data to that specific frequency band with quasi-periodic behaviour. In the case of periodogram, we might then mix the two modes identified via MEMD into one "mode" as it is hard to identify separate modes of variability in a periodogram (see Fig. B3).

Please note that QB and QQ ENSO modes have been identified in the past, thus IMF12,13 are in fact "modes" as they strongly resemble those modes (see l. 282-288).

We hope that changes we have made to the text through this & other comments of the reviewer address also this comment.

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*lines 234-242 discussion of modes IMF12 and IMF13: This description of the time scale behaviour of the modes is not clear. Does it make sense to show the power spectrum of these two modes in comparison to the NINO3.4 SST power spectrum? I assume they both would have strong peaks at the peak in NIINO3.4 SST but have much less variance at all other frequencies?*

This is exactly the case. IMF13 has a peak at about 34 months and IMF12 has a peak at about 22 months, and otherwise their spectra fall sharply away from peak frequency/period. See Fig. S1 (supplement) for periodograms of IMF12,13 and compare it to Nino3 periodogram in Fig. B3. We have also mentioned it in the text - see, e.g., l. 270, 291.

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*line 240 "... (e.g., in Fig. 3b), ...": It is unclear how Fig. 3b relates to what is said in this sentence. Wrong Figure reference?*

Figure reference is correct, but the wording was clumsy. We have changed parentheses to "(e.g., 25-52.5 months band of IMF13 is used to construct band-pass filtered index composites in Fig. 3b; more below)" - see l. 274. Fig. 3b shows a composite for the same fields as Fig 3a, but uses the band pass filtered data with a frequency range consistent with IMF13. This is done for comparison of MEMD with some other method.

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*Analysis of phase: Why do the authors use 12 phases? A cycle is often illustrated by 4 phases (0,90,180,270 degrees). 12 seem to be too much. It would be better to use 0-360 degrees.*

*In Fig.3 and others: How is phase zero chosen? Often phase zero referees to the peak of the reference time series, but here it seems SST is the reference and it is negative at phase 0.*

We use 12 phases to construct line-phase-composite plots, i.e., for smoothing/continuation purposes. Figs. 3,4,6 would look weird with just 4 points so we added 2 additional points between all main phases (also in Fig. 2 for consistency). Phases are chosen as: 0-30 (phase 0), 30-60 (phase 1), ..., 330-360 (phase 11). This has now been clarified - see l. 325-329.

Also, we have now changed composites so that phase 0 is the peak of the composite. Before it was centred at -180 degrees. We have changed references to phases throughout the text accordingly - see track changes.

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*line 288 "... phase of the PC1 (of IMF13) timeseries ...": Unclear what a PC1 in this context means. PC1 is part of the EOF-modes?*

Yes, PC1 comes from EOF analysis described in Appendix A and later used in Appendix B. However, to avoid confusion we have decided to change figures and text so that all composites are based on Nino3 index - for consistency. Again, see, e.g., l. 325-329, and Figure 2 caption.

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*Fig. 3 legend: The legend is not clear. There are several black lines and grey lines. Dashed or dotted cannot be seen in the legend.*

Yes, we have fixed Figs. 3,4,6.

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*lines 491-492 "This suggests an issue ..., since the recharge-discharge mechanism, ... is correctly represented": Logic here is unclear. Where is the issue if it is correct?*

Thank you for pointing this out. The issue here refers to the western Pacific, which seems to have erroneous variability. This is a known model bias/issue. Here, we see it mostly via different phasing of the variables in a phase composite in the model (Fig. 6) relative to observations (Fig. 3a). The eastern Pacific is relatively well represented, although it is too well tuned to the recharge-discharge mechanism (again, a known model bias). We have revised the text accordingly (see l. 528-546). See also Figs. S3-S4 for spatial composites in the model (e.g., warm anomalies during El Nino extend too far west and anomalies are "too" strong).