Reply to Referee #1

On the time evolution of ENSO and its teleconnections in an ensemble view – a new perspective

by Tímea Haszpra, Mátyás Herein, Tamás Bódai

The authors investigate changes in the ENSO phenomenon and its teleconnections using a recently proposed methodology (SEOF). ENSO is the most dominant interannual mode of variability in the climate system: studying changes in its amplitude and its impacts is then relevant to the scientific community. Differently from standard statistical methods in time series analysis, the authors used a new methodology, snapshot empirical orthogonal function (SEOF). SEOF is tailored for ensemble simulations: after a transient time, each member of an ensemble of simulations of a nonlinear dynamical system is believed to cover the distribution of states of the attractor. The authors exploit this to define a new notion of Empirical Orthogonal Function (EOF) along ensemble members, rather than along the time dimension. This methodology allows for the definition of "instantaneous" ENSO patterns. Here the authors consider as "instantaneous" seasonal averages (JJAS and DJF) and proceed in analyzing (a) ENSO pattern and its evolution in time and (b) changes in teleconnections, using the proposed methodology. Changes in the spatial pattern of ENSO (quantified by a regression of the PC of the first SEOF mode on SST) are briefly examined qualitatively and quantitatively by linear fitting the regression maps. Interestingly, the largest changes in patterns are in the JJAS season rather than in DJF. Changes in amplitude of ENSO are also examined. In agreement with previous studies, the authors find an increase in variance of the PC1 and of the Niño 3.4 index. Finally, the authors use the proposed framework to investigate changes in the teleconnection patterns between ENSO and precipitations, using instantaneous and lagged correlations along ensemble members, rather than along the time dimension, and explore the changes of these correlations with time.

This is a well written, clear and interesting paper. Also, the application of the SEOF methodology on ENSO is new. I have some minor comments, mainly regarding the methodology.

Dear Referee #1,

We thank the Referee for the careful reading of our manuscript, and we are glad that the Referee found our manuscript well written and interesting, and that the Referee appreciates the novelty of the SEOF methodology. We are thankful for the Referee's constructive comments on our manuscript. These suggestions have helped improve the presentation and clarity of the paper, and we have incorporated them into the revised manuscript. Here we quote the comments and questions, provide answers and discuss the changes carried out in the text.

(a) The main strength of this methodology is that it allows to analyze large ensembles in a comprehensive and well defined way. Also this framework offers a route to examine teleconnections, disentangling climate variability and external forcing in a correct way.

However, in my opinion, this does not mean that this method is definitively better than traditional time series analysis. Both this methodology and temporal statistics are useful for different reasons. Here some reasons:

Response: We thank the Referee for drawing our attention that a more detailed discussion of the traditional and snapshot frameworks is needed in the manuscript. The Referee's opinion *"this does not mean that this method is definitely better than traditional time series analysis"* led us to clarify the requirements and capabilities of the application of traditional time series analysis tools and those of the snapshot methods. As it is stated in old lines 32–33/in new lines 33–34, stationarity is required for the correct application of the tools of time series analysis, which does not hold in a changing climate. In this case a common practice for separating the forced response of an arbitrary meteorological variable to climate change is to detrend the time series, e.g., by choosing a detrending function (linear, polynomial, exponential, etc.) or applying moving averages over a series of time windows of chosen length. In both cases the choice of the detrending scheme and the length of the time windows brings subjectivity to the analysis, and, furthermore, the results might be misleading (Herein et al. 2017). Even if the process is stationary the choice of a "too short" time period for the analysis may result in detecting false trends (Wunsch 1999, Gershunov et al. 2001, Drótos et al. 2015).

In contrast to this, the snapshot methods, computing statistics at single time instants only from the instantaneous potential states of the climate system, i.e., without the direct effect of previous and future climate states on the statistics of the given time instant, provide a correct way to characterize the plethora of all potential outcomes. These outcomes are compatible with the climate states of the given time instant as determined by an external forcing inducing a climate change, i.e., in the case of processes described by nonstationary statistics. The concept of the snapshot methods with several examples including SEOF analysis was recently reviewed by Tél et al. (2019). In what follows, we detail the changes made to clarify these points in the manuscript.

Drótos, G., Bódai, T., and Tél, T. (2015). Probabilistic concepts in a changing climate: A snapshot attractor picture. Journal of Climate, 28(8), 3275-3288.

Gershunov, A., Schneider, N., and Barnett, T. (2001). Low-frequency modulation of the ENSO–Indian monsoon rainfall relationship: Signal or noise?. Journal of Climate, 14(11), 2486-2492.

Herein, M., Drótos, G., Haszpra, T., Márfy, J., and Tél, T. (2017). The theory of parallel climate realizations as a new framework for teleconnection analysis. Scientific Reports, 7, 44529.

Tél, T., Bódai, T., Drótos, G., Haszpra, T., Herein, M., Kaszás, B., and Vincze, M. (2019): The Theory of Parallel Climate Realizations – A New Framework of Ensemble Methods in a Changing Climate: An Overview. Journal of Statistical Physics (doi:10.1007/s10955-019-02445-7).

Wunsch, C. (1999). The interpretation of short climate records, with comments on the North Atlantic and Southern Oscillations. Bulletin of the American Meteorological Society, 80(2), 245-256.

- It is true that the choice of the time window is largely subjective. However, ENSO has a quasi-periodicity of 3 to 7 years and its teleconnections can be analyzed a 12-months range (e.g., ENSO leads the Western Indian Ocean with a lead lag of ~3 months). I expect that, given a single member, time windows from 30 to 100 years of data would give robust results. If correlations between two basins, start changing when considering 30 or 100 years it can simply mean that the connections analyzed may not be "stable". This is possible in climate and can be a result of (i) local regime shifts in one of the two basins, causing qualitative changes in local dynamics and so in connections with other basins (see Dekker et al.

https://www.earth-syst-dynam.net/9/1243/2018/esd-9-1243-2018.pdf or Klose et al. https://arxiv.org/pdf/1910.12042.pdf) and/or (ii) phenomena of chaotic synchronization between basins (please see this PRL paper from Duane and Tribbia https://pdfs.semanticscholar.org/cd01/9dacfa47fdc2d5b46e8d33dda956fae135b0.pdf). An example of a (possibly) unstable teleconnections is the leading from the Equatorial Atlantic to ENSO. For example, Falasca et al. (https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019MS001654) showed that this lead may exist only in certain decades (see Figures 18e, 18f for reanalyses and Figures 19e and 19f for two CESM members), possibly for phenomena of chaotic synchronization. In the case of this specific teleconnection choosing a window of 50 or 100 years would indeed give a different result, but not because of biases in the methodology but because this connection seems to change in time. Also, in the context of the CESM-LE it has been found at different times in different members, suggesting indeed a chaotic synchronization between the two basins.

Response: We agree on the fact that when only single time series are available, such as measurements or single model simulations, one has to use the traditional methods of time series analysis to analyze the phenomena and obtain results by, e.g. in the case of ENSO, assuming a constant EOF loading pattern for a certain time period and studying its oscillation phases and teleconnections by the corresponding PCs. However, during this time period (e.g., within 30 or 100 years) climate may change, and in the case of the CESM-LE climate change indeed manifests in a considerable global surface temperature increase on decadal time scale (Kay et al. 2015). Therefore, neither it can be presupposed that the pattern of the ENSO or the strength of its teleconnections remain constant (as must be assumed for the traditional approach), nor it can be assumed that a single value of regression coefficient or correlation coefficient can faithfully characterize the conditions of several decades. Indeed, as the Referee writes, "*connections analyzed may not be stable"* and traditional results will not be robust.

However, we do not exactly understand what the Referee means by writing "*choosing a window of 50 or 100 years would indeed give a different result, but not because of biases in the methodology but because this connection seems to change in time*". For the very reasons that (i) the connections change in time and (ii) the traditional approach studies connections (and oscillation patterns, etc.) that are treated as constant for the chosen time period (resulting, e.g., in a single value of the correlation coefficient at each grid point for the time period in which the teleconnection is studied), we do think that, at the very least, the traditional result must be biased in the 100-year window compared to those in 50-year windows, and it will also be biased in any of the 50-year windows in a generic case of time dependence. Of course, this bias results from the limitation that there is no mathematically correct and objective way to overcome this problem with single time series.

Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., ... & Holland, M. (2015). The Community Earth System Model (CESM) large ensemble project: A community resource for studying climate change in the presence of internal climate variability. Bulletin of the American Meteorological Society, 96(8), 1333-1349.

Change: To clarify this issue we have added a detailed description about comparing the capabilities of the snapshot and traditional methods and the meaning of their results as the completely new Section 2.3, more than a page long, including the references emphasizing potential impacts of climate change such as shifting of regimes, chaotic synchronization between different regions and the unstable character of teleconnections. We are grateful for the Referee for drawing our attention to these references.

- Traditional time series analysis (referred in the paper as "temporal statistics") presents lots of desirable tools: (i) different measures of coupling between time series such as linear (e.g., Pearson correlation), nonlinear (e.g., Mutual Information), causal (e.g., PCMCI algorithm) and (ii) robust methodologies to assess statistical significance. This is possible if a large number of data points is analyzed. In the snapshot method, every measure of coupling and every test is constrained by the (very small) number of members of an ensemble. This is a limitation of the methodology since 40 members is still a (very) limited number of data points in the analysis.

Response: We thank the Referee for mentioning that we should draw attention to the limitations of the snapshot methods originating from the small number of ensemble members. We also feel important to repeat here that the desirable tools of traditional time series analysis give robust and unbiased results only if the underlying statistics can be approximated well as stationary. Furthermore, temporal autocorrelation may seriously reduce the effective sample size of the traditional methodology: already with a 3-year autocorrelation, the effective length of a 150-year time series is practically not more than 50 data points.

Change: We have added a discussion on the limitation due to small ensemble sizes to new Section 2.3 immediately after discussing the temporal and snapshot methods according to the previous Referee question.

- More importantly, all results of the snapshot methodology, live in model-land (see http://www.economics-ejournal.org/economics/discussionpapers/2019-23/file). In fact, in reality we have only access to one climate and we have no access to an ensemble. Therefore, the results that can be obtained using this methodology, while interesting, are always going to be constrained to the chosen climate model and its biases. These points should be briefly discuss. Advantages and disadvantages of both the snapshot methodology and traditional time series analysis should be made clear. My view is that they are both useful and can complement each other, and not that one is definitive better than the other.

Response: We thank the Referee for drawing our attention to the importance of emphasizing even more in the paper that snapshot methods can only be applied when an ensemble of climate realizations is available. Most often, such an ensemble is produced by a climate model, however, they may also be accessible in experiments. For example, they proved to be useful in laboratory experiments aiming to study the effect of climate change on mid-latitude atmospheric circulation (Vincze et al. 2017). Obviously, the obtained results are constrained by the climate model or the capability of the experimental setup.

Vincze, M., Borcia, I. D., and Harlander, U. (2017). Temperature fluctuations in a changing climate: an ensemble-based experimental approach. Scientific Reports, 7(1), 254.

Change: We have added the discussion in this Response to the last paragraph of Section 2.3 as well.

(b) Figure 2. Are the trends of the regression maps really linear? Was this checked? I would have expected to be linear in a time range of ~30 years but not necessarily from 1950 and 2100. Can you please check two random time series in the ENSO region and in the Horse

Shoe Pattern (the region with strong negative linear trend) in Fig. 2a and see the shape of the trend?

Response: Although it was not checked, but based on our experience regarding the shape of the time series of the ENSO strength, explained variance of the first SEOF mode and Niño3 amplitude in Fig. 3 we expected that the changes in the regression maps can be approximated by linear trends as well. However, motivated by the Referee's remark, we have checked the time series of two grid points in the ENSO region and two in the Horse Shoe Pattern in Fig. 2, and have found that they can indeed be well approximated by linear trends.

Change: We have added a sentence in old line 134/in new line 228–231 regarding the shape of the trends in the regression maps, and included Fig. S1 to the Supplement in order to provide some examples on the time series of the regression coefficients at different geographical locations.

(c) Figure 3. Panels (b) and (e). It is interesting to see that while the explained variance of PC1 in DJF is relatively constant, this is not true for the season JJAS. In Figure 3b the explained variance of the PC1 experiences a steady increase from ~45% to ~60%. It could be interesting to analyze the second mode of the SEOF and see how it is changing. If this analysis would help in better understanding (or at least suggests an explanation) the increase in variance of the first mode I would recommend to add the analysis of the second mode in the appendix.

Response: Motivated by the Referee's question, we have checked the change not only in the second mode of the SEOF analysis but also in higher modes, up to the fifth one. The increasing values in the explained variance of the first SEOF mode are found to be compensated by the generally slightly decreasing trends appearing in the explained variance of other modes. In JJAS, the second mode contributes the most to the decrease, by 2.4%, while in DJF, for which Fig. 3.e shows a less pronounced increase for the first mode, the explained variance of the second mode is approximately constant, and the compensating decrease appears in the explained variance of the higher-order modes.

Change: These new findings are added to old line 152/to new lines 262–267, and new Fig. S2 is added to the Supplement to demonstrate the change in the explained variance of modes #2–#5.

(d) Figure 5. Second line of the caption. Correct: DJF PRECT (b → DJF PRECT (b)

Change: We thank the Referee, we have corrected it.

We hope that these amendments and added discussion address the Referee's concerns.

Yours sincerely,

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