Reply to Short Comment #1 by Sebastian Milinski

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

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This manuscript provides some interesting ideas by building on previous work that used the ensemble dimension in a large ensemble to describe forced changes in the statistics of the climate system. In particular changes in teleconnections, here characterised by the correlation coefficient in the ensemble dimension, may provide some new insights.

I was wondering why you decided to focus on the first EOF to characterise ENSO variability. Takahashi et al. (2011) argue that both EOF1 and EOF2 should be used to characterise ENSO. Did you test if there are changes in the second EOF? Changes in EOF 2 might also project on the Nino3 region and could theoretically even have an opposing effect compared to the changes in EOF 1 discussed in this manuscript.

Response: Thank you for your comment. As you argue, the EOF2 mode can certainly have a role in the characterization of ENSO variability. Our main intention was to show the applicability and advantages of the SEOF analysis on a simple and easy-to-follow example. Therefore, we investigated the "conventional" EOF pattern of ENSO, i.e., the one associated with the EOF1 mode, following, e.g., Diaz et al. (2001), as mentioned in line 118–121 in the original manuscript. Other studies, e.g., Ashok et al. (2007) (also cited in these lines) confirm that this quantity and the derived PC1 are strongly correlated with the SST variability in the Niño3 region and with the Niño3 index, respectively, while this does not hold for the EOF2 mode and PC2. /Quote from Ashok et al. (2007): "The correlation between PC1 and NINO3 index is very high, and amounts to 0.98, which proves that EOF1 represents the conventional El Niño well. On the other hand, the correlation between PC2 and NINO3 index is very low (−0.09)."/

Nevertheless, motivated by Referee #1, we carried out a new analysis on studying the changes in the explained variance of the EOF2. Fig. S2 in the Supplement illustrates that there is a slight decrease in JJAS, and no significant change in DJF.

Ashok, K., Behera, S. K., Rao, S. A., Weng, H., and Yamagata, T. (2007). El Niño Modoki and its possible teleconnection. Journal of Geophysical Research: Oceans, 112(C11).

Diaz, H. F., Hoerling, M. P., and Eischeid, J. K. (2001). ENSO variability, teleconnections and climate change. International Journal of Climatology, 21(15), 1845-1862.

Change: In order to better support our choice on EOF1, we have added the value of the correlation coefficient found by Ashok et al. (2017) between the PC1 and the Niño3 index to the sentence in old lines 118–121/in new lines 139–141, and we have emphasized that despite the existence of more complex indices for the characterization of ENSO (such as the ones in Takahashi et al. (2011)) we choose PC1 to provide a simple and easy-to-follow example on illustrating the applicability and advantages of the SEOF analysis.

Takahashi, K., Montecinos, A., Goubanova, K., and Dewitte, B. (2011). ENSO regimes: Reinterpreting the canonical and Modoki El Niño. Geophysical research letters, 38(10).

How much does the sampling uncertainty affect the detected changes? I.e. how much of the difference in variance between two years can be attributed to the forcing change and how much of the difference is due to the limited ensemble size? Note that we concluded in Maher et al. (2018) that 30-40 ensemble members are sufficient to quantify ENSO variability when analysing ENSO variability over time periods of 10-50 years. Arguably, 10 years and 30 members might not even be sufficient, depending on the acceptable error (figure 4 in Maher et al. 2018). Since you are using indvidual years, it could be possible that more than 30-40 members are required. Based on this, I would expect to see large sampling uncertainty in the correlation coefficients. It might be beneficial to show the time series for the correlation coefficients for some selected regions to demonstrate that the discussed changes are larger than the sampling uncertainty.

Response: We note that already in Fig. 3 of the previous version of the manuscript trends in ENSO strength, explained variance of the first SEOF mode and Niño3 amplitude proved to be detectable on a traditionally computed 95% significance level using the CESM-LE. It means that 30-40 members over the studied 150 years with the prescribed RCP8.5 forcing proved to be sufficient to detect the changes in the time series despite the considerable magnitude of the fluctuations due to the sampling uncertainty deriving from the number of ensemble members.

Change: Motivated by this question, we indicate in all of the map figures of the new version of the manuscript the geographical locations where correlations or detected trends are significant at the traditionally computed 95% level. Based on these data, we may safely state that the number of ensemble members in this study is sufficient to characterize the strength of the teleconnections reasonably well and to detect the changes during the investigated 150 years.

As the statement regarding the number of ensemble members was the result of a misunderstanding in this context in line 88 of the original manuscript/in line 101 of the revised manuscript, we deleted this part of the sentence in the new version.

Separating amplitude and pattern changes: In figure 1, you standardised the PC1. Thus both pattern and amplitude changes, if they occur, can be seen in the regression maps. Did you use the same approach for the analysis in figure 3? An alternative approach to separate pattern and amplitude changes would be to normalise the pattern. Amplitude changes can then be seen in the PC, whereas pattern changes can be seen by comparing the regression maps for different states of the climate system. This is the approach we used in Maher et al. (2018).

Response: We would like to note that, as it can be seen from the values and the unit, in Fig. 3 PC1 is not standardized, rather it includes the mentioned separated amplitude of the oscillation.

Besides studying the separated amplitude of the ENSO phenomenon, we felt more intuitive and meaningful to present regression maps and analyze the changes in them, as these maps show the typical value of the amplitude of the fluctuations directly related to the given EOF mode of variability at each grid point, which in the case of EOF1 has the strongest relationship with ENSO. The changes in the regression maps are then easy to interpret: they show the changes in these fluctuation amplitudes, i.e., changes in the typical SST anomalies bound to the given mode at each grid point, and potential shifting in the pattern during climate change as well.

In contrast to this, from normalized patterns or EOF loading patterns the value of the typical SST anomalies bound to the given mode cannot be seen, just the fact that at some locations they are somewhat greater than at other ones or are in the opposite phase at a given time instant. The changes in these normalized patterns show the changes in the relative importance of different regions over time from the point of view of the given mode. Motivated by the comment, we carried out the analysis of the separated pattern as well, using the raw SEOF loading patterns (by which we mean the normalized eigenvectors associated with the largest eigenvalue of the covariance matrix of the SST anomaly fields).

Change: As we feel more intuitive to illustrate the changes in the ENSO pattern by regression maps, we keep them in the new version of the manuscript. However, as a supplement to the regression maps, we have added Fig. S3 to the Supplement containing the maps of the first SEOF modes (SEOF loading patterns) for the years in Fig. 1. We have also carried out the linear regression analysis at each grid point, analogously to Fig. 2, to track the changes in the separated pattern. These are displayed in Fig. S4. The interpretation of these results are added in old line 142/in new line 238–250.