# The impact of greenhouse warming on the El Niño–Southern Oscillation (ENSO): a new method for ENSO teleconnection analysis

Final Report
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*A new method for ENSO teleconnection analysis*

One of the greatest global challenges of our times is the better understanding of the ongoing climate change and its consequences, especially in terms of variability. Due to the vast complexity of the Earth system, the main scientific questions related to this issue address the *statistical properties* of the dynamics, and transitions they undergo as a result of climate change. The proper statistical treatment of fluctuations and long-range correlations in the coupled ocean-atmosphere system subjected to a temporally evolving forcing is far from being trivial. The very definition of climate – in the traditional sense – is based on long-term statistics of various state variables (i.e. in a typical window of 30 years), tacitly assuming that the ongoing processes can be considered stationary on such a longer timescale. However, in reality, the driving forces and boundary conditions ($CO_2$ concentration, solar irradiance, etc.) are themselves changing in time, complicating the interpretation of the statistics. Therefore, to gain a deeper insight to the underlying basic processes and to separate their statistical signatures, it is essential to conduct conceptual numerical experiments in which the components of the coupled ocean-atmosphere system can be investigated under changing but controllable and reproducible conditions. This research offers a new way (based on *snapshot attractor view* (Romarias et al., 1990; Ghil et al., 2008; Drótos et al., 2015; Herein et al., 2016; Tél et al., 2019)) to avoid the hindering consequences of any temporal based statistics and presents new results, especially focused on teleconnection analysis. In this final report we do not go into details why our snapshot method is a unique option in a changing climate situation, however, the whole concept along with the mathematical background and the applicability in general circulation models can be found in Herein et al., 2016 and Tél et al., 2019. Teleconnections are part of climate variability and the question naturally arises; how to characterize them under changing climate conditions. This is the first research in which this question is discussed and a solution is provided following the "Theory of parallel climate relizations" (Herein et al., 2017; Tél et al., 2019).

In this research a crucial point was how the ENSO and its teleconnections would change as a result of the increasing radiative forcing due to the increasing greenhouse gas concentrations. The general problem is that mostly temporal averaging is used to predict the behaviour of the ENSO, however generally in a changing climate, where one or more relevant parameters are changing in time, there can be no stationarity by definition, whereas stationarity is crucial for the applicability of temporal averages. As a start the relationship (teleconnection) between the ENSO and the Indian summer monsoon in an ensemble-based framework, has been investigated. The ensembles are produced by state-of-the-art climate models, the Max Planck Institute Earth System Model (MPI-ESM) and the Community Earth System Model (CESM). We considered two simple variables: the Tahiti–Darwin sea-level pressure difference and the Northern Indian precipitation, since this is a widely used method to capture the dynamics of the ENSO and because it lacks the need of statistical preprocessing, thus avoiding possible corresponding ambiguities. The Northern Indian precipitation is especially important, since the climate change has an enormous impact on it. Both models agree that the Northern Indian precipitation (during the Indian summer monsoon) will significantly increase due to the climate change. However the teleconnection between the Northern Indian precipitation and the ENSO proved to be a complex phenomenon. We defined teleconection strength as an ensemble based instantaneous correlation, we call it $SOI_e$. or $SOI(p_{diff})$; the details of the computations can be found in Bódai et al., 2020.

We found that the MPI-ESM satisfactorily reproduces the expected features of the teleconnection, while the CESM behaves more unexpectedly. In the MPI-ESM, the teleconnection undergoes a considerable strengthening in the modelled historical period, concentrated to the last decades of the simulation. In the same model, however, change is detected neither between 2006 and 2099 under the RCP8.5, nor in a time interval of 110 years under a 1-percent pure $CO_2$ scenario — in both of the latter scenarios, the radiative forcing is practically always higher, and covers a much wider range than in the historical forcing scenario. Furthermore, change is not detected in the 1960-2100 time interval simulated according to historical forcing and the RCP8.5 in the CESM either. This result suggests that the teleconnection system (ENSO) survives the climate change and remains stable. At the same time it is also important that the teleconnections could be time-depended as well. As a main result with very high confidence, we detected an increase in the strength of the teleconnection, as a response to the forcing, in the MPI-ESM under historical forcing (MPI-HE) between 1890 and 2005, concentrated to the end of this period. In the MPI-ESM we could not reject stationarity between 2006 and 2099 under the Representative Concentration Pathway 8.5 (RCP8.5), and in a 110-year-long 1-percent pure $CO_2$ scenario; neither can we in the CESM between 1960 and 2100 with historical forcing and RCP8.5. In the latter ensembles, the climatic mean is strongly displaced in the phase space projection spanned by the two variables. This displacement is nevertheless linear.

From an analysis of the sensitivity of the hypothesis tests of stationarity (Mann-Kendall test), we have shown that the strength of the teleconnection cannot respond to radiative forcing instantaneously and linearly, since our tests would have had to detect nonstationarity in the ensembles other than MPI-HE, too. It is remarkable that our curious result, namely the increasing teleconnection strength in the XX. century, is contrasting existing literature. (Bódai et al., 2020).

We also characterized ENSO by the traditional JJA (June-July-August) Niño 3 box-average SST and the IM (Indian monsoon) by the JJAS (June-July-August-September) average precipitation over India, and defined their teleconnection in a changing climate as an ensemble bsed correlation. To test robustness, we also considered somewhat different variables that can characterize ENSO and the IM. We utilized ensembles converged to the system's snapshot attractor for analysing possible changes in the teleconnection. Our main finding is that the teleconnection strength is typically increasing on the long term in view of appropriately revised ensemble-wise indices. Indices involving a more western part of the Pacific reveal, furthermore, a short-term but rather strong increase in strength followed by some decrease at the turn of the century. Using the station-based $SOI_e$ (as in the first year of the research) as opposed to area-based indices led to the identification of somewhat more erratic trends, but the turn-of-the-century "bump" is well-detectable with it. After the comparison to results produced by traditional methods, the remarkable result is the all this is in contrast, if not in contradiction, with the discussion in the literature of a weakening teleconnection in the late 20th century. We think that this discrepancy can be due to any of three reasons: ensemble-wise and temporal correlation coefficients used in the literature are different quantities; the temporal moving correlation has a high statistical variability but possibly also persistence; or MPI-ESM does not represent the Earth system faithfully (Bódai et al., 2020).

It is known and used widely in the climate community that ENSO's patterns can be computed via emphrical orthogonal function analysis (EOF). Using EOF not just the point-wised correlations but the correlation field can be computed, which is very beneficial to be able to study spatial patterns of the correlation map. If one considers EOF technique it is can be seen that it uses temporal averaging, which is problematic at least in a changing climate. Therefore we developed the first ensemble based version of EOF, which we call SEOF (snapshot EOF). SEOF can be used to calculate instantaneous patterns of any known climate oscillation and its teleconnection. It works in the ensemble dimension and correlation maps can be computed across the ensemble, as well. The background and details of the SEOF method can be found in Haszpra et al., 2020a.

Using SEOF method we investigated the changes in the ENSO phenomenon and the alterations of its precipitation-related teleconnections for 1950–2100 in the CESM-LE climate simulations. SST data is utilized to reveal changes in the pattern and amplitude of the ENSO. Instantaneous ensemble-based correlation coefficients between the principal components (PC1s) of the first SEOF mode (considered as an index for the ENSO phase) and the total precipitation at each grid point over the globe were also determined to evaluate ENSO's precipitation-related teleconnections. Our results show that the ENSO pattern undergoes remarkable changes during the investigated time period. This is found to be more pronounced in the JJAS season, where the ensemble-based SST regression maps even show 0.45 and −0.45 ∘C changes in the Niño3–Niño3.4 region and in the western part of the Pacific Ocean over 150 years, respectively. These changes are of the same order of magnitude as the typical SST variability across the ensemble at different time instants, which is found to be of 0.5–1.5 ∘C in the equatorial region.

The Niño3 amplitude also increases by about 20 % and 10 % in JJAS and DJF, respectively. We also found clear growth at a similar rate in the ENSO strength (defined as the ensemble standard deviation of the PC1s) and in the explained variance in the first SEOF mode. This means that the amplitude of the fluctuations in the SST field will increase, and the first SEOF mode will explain a much larger fraction of the variability in the SST fields by the end of the 21th century. In general, a larger change in the different quantities is found for JJAS than for DJF. While at the beginning of the JJAS season the ENSO cycle is generally just switching phase in the CESM-LE, DJF can be considered to be the "main" ENSO season with the largest SST anomalies. The smaller changes in the DJF quantities may be explained by the conjecture that, calculated for the main ENSO season, the DJF characteristics may be more robust and, thus, undergo weaker alterations during the investigated 150 years than during the JJAS ones, which are calculated around the phase change in the cycle.

We focused on the precipitation-related teleconnections of the ENSO, they show a considerable change over time in several regions. Instantaneous correlation maps were calculated by SEOF method. For example, the anticorrelation with precipitation in Australia and on the southern edge of South America in JJAS are predicted to be more pronounced by the end of the 21th century, as it changes from about −0.5 by −0.15. At the same time, the positive correlations in central Africa and the western coast of South America, especially in Chile, become enhanced by 0.15–0.3, as well. Lagged correlation coefficients reveal potential predictability of the precipitation conditions based on ENSO's PC1. We found that the amount of precipitation in Australia, New Zealand, and Indonesia in JJAS is generally less than average after DJF warm episodes, while, e.g., the eastern coast of Africa is wetter than average. In DJF the amount of precipitation in Australia and in southern India is less than average after previous warm conditions in JJAS; however, the central islands in Indonesia and a large part of eastern and central Africa get more precipitation. Our results show that the strength of these connections strengthens over time, especially in the African region up to the Arabian Peninsula and slightly in southern India (Haszpra et al., 2020b).

We emphasise that our SEOF lacks any temporal statistics for the EOF analysis and correlation calculation for revealing teleconnections; thus, it is an objective way to explore the time evolution of other phenomena (climate oscillations) and teleconnections under climate change. It is to be mentioned that our SEOF method was selected by Clara Deser (NCAR, USA) to contribute to the 2020 summer edition of US CLIVAR Variations on Large "initial condition" Ensembles (Haszpra et al., 2020c).

We briefly mention that the wavelet analysis of the ENSO produces the known 4-7 year characteristic period, however, the wavelet ensembles do not seem to provide any novelty to the existing literature.

The main message of this research is that the ENSO's future dynamics cannot be understood without the use of large ensembles. In addition it is not enough to run ensembles but we need improve our knowledge about ensemble statistics. In this direction a very first step is to apply snapshot methods, like SEOF to gain a firmly established picture about the future of the ongoing climate change.

### *Joint research*

The snapshot method can be widely used in Earth Sciences, especially, where relevant parameters are time-dependent. In the following we mention some research topic in which the snapshot method proved to be effective.

Based on SEOF analysis we have shown that the traditional method for computing the AO index (Arctic Oscillation index), which uses traditionally a single climate realization, results in values that strongly depend on the choice of the reference period. Our ensemble based results emphasize that the AO and the related surface temperature patterns are non-stationary and their time evolution depends on the forcing. The AO's amplitude increases and the Pacific centre strengthens considerably. Additionally, there exist such regions (e.g., northern Europe or western North America) where the ensemble based correlation shows remarkable change (0.2–0.4) by 2099. (Haszpra et al., 2020a).

As a continuation of our teleconnection research we utilized five available large "initial condition" Earth system model ensembles and 31 CMIP5 models' preindustrial control simulations to understand Arctic's summer ice melting processes due to internal variability. According to both observations and CESM-LE simulations there is a regional barotropic atmospheric process over Greenland and the Arctic Ocean in summer, featuring either a year-to-year change or a low-frequency trend toward geopotential height rise, has been identified as an essential contributor to September sea ice loss. However, we found all investigated models exhibited limitations in replicating the magnitude of the observed local atmosphere–sea ice coupling and its sensitivity to remote tropical SST variability in the past four decades. We claim that these biases call for caution in the interpretation of existing models' simulations and fresh thinking about models' credibility in simulating interactions of sea ice variability with the Arctic and global climate systems (Topál et al, 2020).

As an outlook we studied atmospheric spreading in two ensembles of climate realizations, produced by the PlaSim (Planet Simulator) and CESM climate models (we note the second one is the same which has been used in ENSO analysis), simulating century-scale climate change. We showed that the intensity of the atmospheric large-scale spreading can be well characterized by a measure of chaotic systems, called topological entropy. We found that pollutant clouds stretch in an exponential manner in time, and in the atmospheric context the topological entropy corresponds to the stretching rate of its length. An overall decrease in the areal mean of the stretching rate is found to be typical in the ensembles of both climate models. The notable result is that the larger pollutant concentration for several geographical regions implies higher environmental risk. We showed that the typical intensity of the spreading in an arbitrary climate realization can be estimated by using only the ensemble means of the relative vorticity data of a climate model (Haszpra & Herein, 2019)

Another outlook where our ensemble based statistical view proved to be crucial, was an investigation of snowball Earth dynamics. Using climate model PlaSim, we investigated the snowball Earth transition.

For certain values (including today’s value) of the solar constant, the climate system allows two different stable states: one of them is the snowball Earth, covered by ice and snow, and the other one is today's climate. We considered the case when the climate system starts from its warm attractor (the stable climate we experience today), and the solar constant is changed according to the following scenario: it is decreased continuously and abruptly, over one year, to a state, where only the Snowball Earth's attractor remains stable. This induces an inevitable transition, or climate tipping from the warm climate. The reverse transition was also discussed. Increasing the solar constant back to its original value (in a similar way), in individual simulations, depending on the rate of the solar constant reduction we found that either the system stays stuck in the snowball state or returns to warm climate. However, using ensemble methods i.e., using an ensemble of climate realizations we showed that the transition from the snowball Earth to the warm climate is also possible with a certain probability which depends on the specific scenario used. From a dynamical systems theory point of view, we can say that the system's snapshot attractor splits between the warm climate's and the snowball Earth's attractor.

We also showed that the transition process is probabilistic and the probabilities of the corresponding outcomes are given by the ensemble’s distribution. In addition, the third, unstable state of the Earth’s climate (referred to as the edge state) was also discovered (Kaszás et al., 2019).

Lastly we mention that a review article about our ensemble based, snapshot method has been published. We showed that important features of the climate change we are observing can be understood by imagining many replicas of the Earth that are not interacting with each other. One chapter in the review is for teleconnections with all the basic ideas about the ensemble based analysis of the well-known teleconnections (Tél et al., 2019).

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## Media appearance

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## Publication activity

The results were published in 8 articles in peer-reviewed journals (IF = 29.265) and presented in 3 solicited talks, 12 talks and 4 posters at international conferences, and in 3 miscellaneous talks.