Earth Syst. Dynam. Discuss.,
https://doi.org/10.5194/esd-2019-50-AC1, 2020

Earth System Dynamics
Discussions

Interactive comment on "Spatial Signature of Solar Forcing over the North Atlantic Summer Climate in the Past Millennium" *by* Maria Pyrina et al.

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Received and published: 22 January 2020

First of all the authors would like to thank Referee 1 for agreeing to review this manuscript. We appreciate the effort and the comments, which, we are sure, will significantly improve the current manuscript.

The motivation for the present study was that the influence of solar forcing over the past millennium has been detected in marine proxies for the Sea Surface Temperature (SST) of the North Atlantic (NA) region in centennial and multi-decadal time scales (Jiang et al., 2005; Moffa-Sánchez et al., 2014; Sejrup et al., 2010). Therefore, in the current version of the manuscript, we wanted to test whether 1000-year long solar only forced climate simulations also show this influence and at which time scales (inter-

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annual, decadal) can be detected. It is important to use solar only forced simulations especially because of the low TSI scaling used in our study, which is the current standard value used for solar forcing in many CMIP5 simulations (Kopp and Lean, 2011; Prša et al., 2016). The low TSI scaling might most likely be the reason why the solar signal does not appear robust and difficult to discriminate from internal variability. Our analysis does, therefore, provide a scientific contribution since it shows that the interpretation of the proxy signals in the aforementioned papers is not totally consistent with the modelling results.

In a revised version of the manuscript we will refocus the manuscript and we will robustly show whether we identified a solar forced response in the 1000-year long simulations, and discuss the implications that this might have for comparisons between models and proxy data. We will therefore implement an additional chapter specifically dedicated on the discrimination between internal and solar forced signals. This result is important in order to support or put into question the interpretation of the solar signal in proxy records. Our null-hypothesis will be that the CESM simulations do not show any response to changes in solar activity. The null-hypothesis will be tested through point wise correlations between the individual CESM ensemble members. The null-hypothesis can eventually be rejected for those regions (taking care of global significance) showing correlations exceeding the 5% significance level. The CESM solar only forced ensemble members are forced with the same TSI forcing (they differ slightly in the initial conditions), therefore regions with significant values of temporal correlations among the members will be identified as regions that respond to the common forcing. In the case that we identify a robust solar signal, then for determining the time scales of the signal we will additionally use cross-wavelet analysis of the climatic variable and solar forcing, for the NA sub-regions that are indicated by the CESM ensembles as regions with commonly forced signal. To test the significance of the periodicities of the signal, we will investigate the existence of similar periodicities in synthetic time series with prescribed statistical properties.

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The variables that will be analyzed will be the SSTs (motivated by the aforementioned proxy studies) and the turbulent heat fluxes (key parameters for the interactions between ocean–atmosphere and the transmission of a possible solar signal). We will also investigate variables related to atmospheric dynamics that were shown to respond to solar forcing by previous studies for winter circulation (i.e. sea level pressure, zonal wind; Thieblemont et al., 2014). All of these variables were already analyzed in this manuscript but not appropriately presented, according to both of the Reviewers' comments. The main conclusion is that the solar signals are not robust in these variables either, and therefore no robust physical mechanisms during summer can be identified. We believe that a revision of this manuscript will still be inside the time guidelines of a major revision. In the following, we provide a point-by-point answer to the Reviewer's comments.

Answers to the reviewer's comments on 1. Data and Methods:

1) We will follow the reviewer's recommendation and include a table with the models, experiments, forcing data and ensemble members involved in this study. Regarding internal variability, we agree with the reviewer that the ensemble mean of the solar forced CESM experiment provides a possible way to distinguish the solar signal from internal variability. Nevertheless, it might be that a large number of the ensemble members is needed in order to do so and that this number depends on the problem (Maher et al., 2018) and region (Bengtsson et al., 2019). Moreover, not all ensemble members should be equally represented in this mean (Wanders and Wood 2016). The CESM solar only forced ensemble provides four ensemble members, the ones analyzed in the current study. In this study, we show the response patterns estimated from the individual ensemble members and how these patterns might vary due to the effect of the different realizations of internal variability that each of the members contains. In this way, we can better compare model results to results from empirical studies, as this approach is more representative regarding the uncertainty in the forced response arising from internal climate variability. However, as stated in the line 321, we have provided

in the Appendix of the current manuscript the CESM ensemble mean response for all methods and variables (SI Figure S13).

2) All the experiments presented use the same TSI forcing, which is the Vieira et al., (2011) total solar irradiance reconstruction (referenced in lines 227, 232). In the revised version of the manuscript, this will be clearly shown in a table and it will referenced in Figure 1.

3) Regarding the inter-annual time scale there is no filtering of the data. The low-pass filter was applied on the variables (SST, SLP, geo500) in order to isolate the signals with a frequency lower than the selected cutoff frequency (fmax=1/11 in our case). Therefore, variability was suppressed for time scales shorter than 11 years. The design of the filter is cited in the manuscript (line 156). There was no filtering applied on the TSI data because the physical resolution of the reconstructed TSI record is already decadal (Vieira et al., 2011), due to the resolution of the ice-core records. Additionally, there was a mistake on the text referring to an "eleven-year running mean filter", when actually it should have been referred to as "eleven-year low pass filter", as stated in the next sentence (line 156). The reviewer is correct that after low-pass filtering, not only the decadal, but also the inter-decadal and longer time scale variability will be retained, but the effect of these time scales is not expected to affect the results of this study on decadal time scales.

4) Regarding composite analysis we agree with the reviewer about stating the number of years involved in the high and low TSI respectively and adding some indications on Figure 1 about the high and low TSI values. The composite results are given only for inter-annual time scales, as the results of this method will not be interpretable after low pass filtering the data. Therefore, the climate variables (SST, SLP, geopotential height) were not low pass filtered prior to composite analysis. This will be also specified in the new manuscript version.

5) In the last paragraph of the section 2.1 Methods, we mention the significance tests

used for all methods: “A two-sided Student’s t-test that accounts for the effect of serial correlation was applied on the results of the linear methods. A mean difference two-sided test was also conducted to evaluate the statistical significance of the results according to the methods MCA minus LIA and composite analysis.” We agree though that we do not clarify that the significance tests were indeed performed for each individual grid point. Regarding the field significance of our results, we will apply a field significance test for identifying whether the basic conclusions of our results are robust. This can be achieved through Monte Carlo temporal re-shuffling in order to retain the spatial auto-correlation of the climate fields.

Answers for the reviewer’s comments on 2. Results and Discussion:

1) The E1, E2, E3, E4 experiments are the ensemble members of the: solar only forced experiment with CESM (lines 160-162). We will make clear in the new version of the manuscript that the difference in the CESM ensemble members is only the slightly different initial conditions. As described in the discussion, there are studies that use regression and correlation to show the relationship between solar forcing and climate. Here, we tried to show that internal variability might be stronger than the signal itself, which would have important implications for the comparison of model output to the results of empirical studies and the interpretation of the identified proxy signals. The individual CESM ensemble member response patterns to solar forcing are shown in Figures 1-4 and the ensemble mean response pattern in the Appendix Figure S13, as stated in the manuscript (line 321). The illustration of the signal derived from individual members is useful to provide a measure of the impact of internal variability. Regarding the interaction of solar forcing with summer surface climate, there is a separate section (3.4) that includes only the results drawn using composite analysis.

2) The results of composite analysis regard high TSI years minus low TSI years, as stated in line 313. We believe that this reviewer’s comment will be addressed in the new version of the manuscript where the data and methods sections will be clearer for the reader.

3) As the reviewer suggests, in the new version of the manuscript we will further discuss how the “high-frequency” internal variability blurs the estimation of the response to the external forcings.

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