Final Report for Project **1148**
Project title: **SOLCHECK**
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Solar contribution to climate change on decadal to centennial timescales (SOLCHECK)

The SOLCHECK project was funded as a sub-project of the funding measure "Role Of the MIddle atmosphere in Climate (ROMIC-II)". The aim of this funding measure was to understand and quantify the solar contribution to the past, present and future climate development in the northern hemisphere on time scales of decades to centuries. SOLCHECK thus contributes directly to the objectives of the ROMIC-II funding measure through:

- Assessing the role of natural solar variability in observed and future global and regional climate change
- Examining the potential impact of extreme scenarios, such as a “Grand Solar Minimum” and other extreme solar events, on climate development
- Assessment of solar forcing for climate predictability on the decadal time scale

The Max Planck Institute for Meteorology has contributed to these goals in particular by carrying out both existing (CMIP6) and new model simulations with the operational German decadal forecast system MiKlip and evaluating them with regard to forecast skill.

1. Project overview

Observational and modeling studies indicate a significant influence of solar variability on climate and in particular on internal climate variability modes in the coupled atmosphere-ocean system. However, the understanding of the relevant processes as well as the quantification of solar contributions to global and regional climate change remains a difficult task due to the limited availability of observations and the non-linearity of the involved processes. SOLCHECK aims at significantly advancing the understanding and quantification of the solar contribution to past, present, and future climate evolution in the Northern Hemisphere from decadal to centennial timescales. The research questions of SOLCHECK have been addressed using German community models. In addition to the German decadal climate prediction system MiKlip (Marotzke et al. 2016), chemistry-climate models were applied that account for atmosphere-ocean feedback processes and include advanced schemes for the ozone response to solar variability, partially developed in ROMIC-I. Our approach is unique in several aspects: 1) the realization of ensemble simulations with advanced chemistry climate models for different combinations of fixed or transient anthropogenic and solar forcing conditions provides an unprecedented statistical basis for the assessment of solar forcing contributions to decadal climate variability and climate change, 2) performing ensemble simulations with the MiKlip system with and without solar forcing provides for the first time a robust estimate of solar contributions to decadal climate prediction skill, and 3) a range of the potential impact of a future Grand Solar Minimum and other extreme solar events under different greenhouse gas scenarios are provided. The outcome of SOLCHECK is highly relevant to the WCRP Near-term Climate Prediction Grand Challenge and the upcoming IPCC report, and will provide the German contribution to the international WCRP/SPARC-SOLARIS/HEPPA initiative.

2. Results

2.1 Historical simulations without solar variability

To assess the role of solar variability on the climate, the historical simulations without solar forcing are compared to the historical CMIP6 simulations from the MiKlip project (Marotzke et al. 2016), i.e. including the long-term solar variability (long-term trend) and the 11-year solar cycle. Phases with observed positive and negative radiation anomalies are defined and the difference between the zonally averaged zonal wind (u) and the zonally averaged temperature (T) is analyzed with regard to the phases of strong and weak solar radiation (formation of so-called composites).

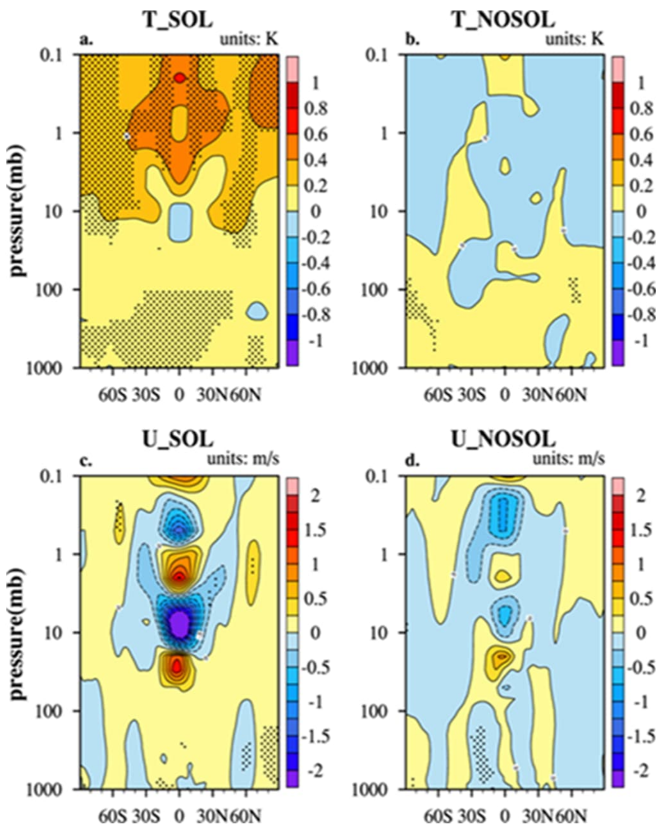

Figure 1: *Sections of the annual and zonal averages of the ensemble mean from 8 historical simulations with MPI-ESM-HR included (a, c) and without the 11-year solar cycle (b, d) for temperature [K] (a, b) and zonal wind [m/s] (c, d). The difference in temperature or zonal wind between strong and weak solar radiation (max-min) is shown. Points indicate the 90% significance (determined via boot-strapping).*

Figure 1 shows that the solar cycle has an influence on the quasi-biennial oscillation (QBO) in the stratosphere (Figure 1c). This pattern disappears almost entirely if the solar cycle is not considered in the simulations and solar irradiance is kept at a constant level (Figure 1d). Furthermore, a warming signal (Figure 1a) can be seen in the upper stratosphere, which is known from previous model studies (e.g. Mitchell et al., 2015).

2.2 Historical simulations with long-period solar forcing

To evaluate the role of long-term solar variability, the potential predictability variance fraction (ppvf; Boer, 2004) is considered, which is a measure of the proportion of the required (here long-period) variance in the total variance of a selected climate parameter. Figure 2 shows the ppvf from 1932-2013 for the average of surface temperatures over eight consecutive winters in the CMIP6 simulations (a, “FULL”) and in the low-pass filtered solar forcing experiments (b, “LOWFREQ”) and the difference in the ppvf of both ensembles (c).

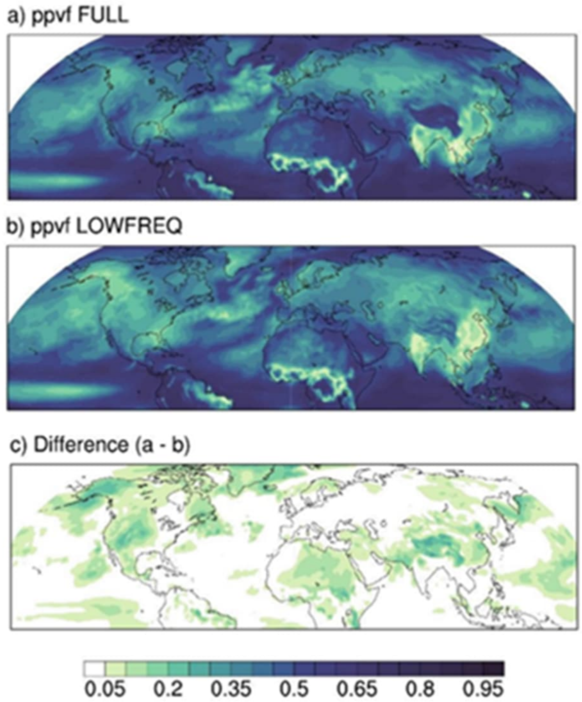

Figure 2: *Potential predictability variance fraction (ppvf) over the mean surface temperature in winter in the CMIP6 simulations (a) and in the experiments with low-pass filtered solar forcing (b) and their difference (c). The surface temperature was averaged for the period 1932–2013 over the months of December, January, February, a running averaging window (8 years), and the respective ensemble.*

In the north-western North Atlantic as well as in the eastern Pacific and over North America there is an influence of the 11-year solar cycle on the decadal predictability; here up to 25% of the variability on the decadal time scale can be attributed to the solar cycle (c). The regions with increased ppvf in MPI-ESM-HR differ from the regions identified in the study by Drews et al. (2022) based on the “Whole atmosphere community climate model” (WACCM). Particularly for mainland Europe (a region strongly influenced by the North Atlantic Oscillation), no improvement in forecast quality can be observed by adding the 11-year sunspot cycle. A solar influence on the North Atlantic circulation cannot be determined in the MPI-ESM-HR simulations.

2.3 Assessment of solar influence on skill in decadal simulations

The underlying high-resolution model MPI-ESM-HR (Müller et al., 2018) is the basis of the MiKlip prediction system and thus also of the decadal prediction experiments carried out in SOLCHECK without variability in solar radiation. The aim of these experiments was to identify and quantify the contribution of solar irradiance to real decadal forecasts, such contributions were already found in the historical simulations and, among others, in the experiments by Drews et al. (2022) and were postulated to be of significance. The ensemble of retrospective decadal prediction experiments includes 10 members and differs from the corresponding CMIP6 predictions only in the solar forcing, with the forcing only including the annual cycle of 1850 and no long-period variability. A 10-year ensemble forecast was initialized every November 1st from 1960–2013.

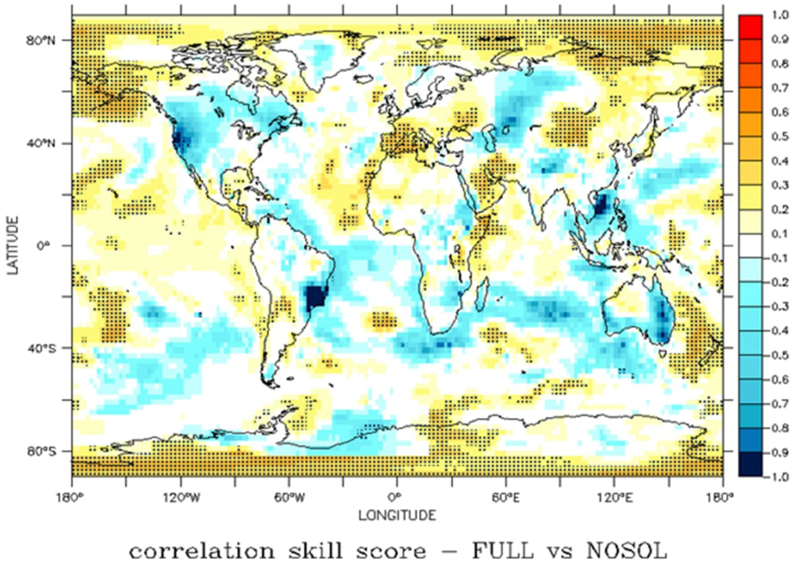

Figure 3: *Correlation skill score (CSS) of the annual mean global surface temperature for the forecast horizon 2 to 5 years of the ensemble forecasts, each initialized on November 1st from 1960 to 2013. Comparison of the CMIP6 decadal forecasts (FULL) to the forecasts with suppressed variability in solar forcing (FIX). Correlations were determined using observations from GIStemp v4 (Lenssen et al., 2019). Points indicate 95% significance, determined via bootstrap sampling.*

For an assessment of the predictive quality of the retrospective forecasts with full forcing (including variable solar irradiance), a correlation skill score (css) of the annual mean global surface temperature was calculated for the forecast horizon of 2 to 5 years (Figure 3). The experiments without solar variability are considered a reference prediction for determining the skill score; the observed surface temperature comes from the GISTem v4 data set (Lenssen et al., 2019). A positive skill score indicates improved forecast quality, which can be directly attributed to the contribution of solar radiation. Remarkably, a significant improvement in forecast quality is present in the polar regions and, at lower latitudes, in selected land regions such as southwestern Europe, New Zealand, Mongolia or parts of the Middle East. However, the areas of significantly improved forecast quality in the Atlantic and Pacific Oceans do not correspond to the postulated regions from the analysis of historical experiments and, contrary to expectations, North America also does not show any improved forecast quality. However, the positive skill score, which can be seen in large parts of the tropical and subtropical Pacific Ocean, indicates a possible influence of solar radiation on the prediction of the ENSO phenomenon, a predictor for many other climate phenomena worldwide, although the improved prediction quality in the eastern equatorial Pacific, the core region of ENSO, is not significant (Kröger et al., 2024, in progress).

3. Summary

The scientific results achieved in SOLCHECK reduce the uncertainties in future climate predictions, as the contribution of solar variability to the prediction skill in decadal prediction systems is now better quantified. This results in knowledge gain for long-term climate modeling and climate predictions, such as those planned as part of CMIP7.

4. Data storage and usage plan

The simulations with MPI-ESM-HR were carried out on the high-performance computer of the German Climate Computing Center (DKRZ). The data archiving and publication took place in collaboration with the DKRZ (Pohlmann, 2021; Kröger & Pohlmann, 2022a, b).

5. Publications

Kröger, J. & H. Pohlmann, 2022a: SOLCHECK MPI-M MPI-ESM1-2-HR CMIP6 historical simulation with low-pass filtered solar and ozone variability. doi: 10.26050/WDCC/SOLCHECK_MPI-ESM-HR_C6_lowpass

Kröger, J. & H. Pohlmann, 2022b: SOLCHECK MPI-M MPI-ESM1-2-HR CMIP6 retrospective forecasts (hindcasts) without solar and ozone variability. https://www.wdc-climate.de/ui/entry?acronym=DKRZ_LTA_1148_dsg0001

Kröger, J. et al., 2024: Estimating the solar contribution to climate prediction skill. (in progress)

Pohlmann, H., 2021: SOLCHECK MPI-M MPI-ESM1-2-HR CMIP6 historical simulation without solar and ozone variability. doi:10.26050/WDCC/SOLCHECK_MPI-ESM- HR_C6_hist

Spiegl, T. C., U. Langematz, H. Pohlmann, J. Kröger, 2023: A critical evaluation of decadal solar cycle imprints in the MiKlip historical ensemble simulations. Weather and Climate Dynamics, 4, 789–807. doi:10.5194/wcd-4-789-2023

6. References

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Lenssen, N. J., Schmidt, G. A., Hansen, J. E., Menne, M. J., Persin, A., Ruedy, R., & Zyss, D. (2019). Improvements in the GISTEMP uncertainty model. Journal of Geophysical Research: Atmospheres, 124(12), 6307-6326. https://doi.org/10.1029/2018JD029522.

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Müller, W. A., Jungclaus, J. H., Mauritsen, T., Baehr, J., Bittner, M., Budich, R., ... & Marotzke, J. (2018). A higher-resolution version of the max planck institute earth system model (MPI-ESM1. 2-HR). Journal of Advances in Modeling Earth Systems, 10(7), 1383-1413. https://doi.org/10.1029/2017MS001217.