Project Report for Project 4

BERN03 - Introduction to Modelling of the Climate System

Assessment of solar forcing and its effect on seasonal climate variability in the Northern Hemisphere

Author

Pim Nelissen

Department of Geology

Faculty of Science

Lund University

January 17, 2025

1 Introduction

The effect of solar radiation on climate variability is well known, but the exact magnitude of its influence is debated [1, 2]. In this paper, two different climate model ensembles, one with a weaker and one with a stronger solar forcing, are explored. The goal is to see how the difference in solar forcing affects variability in climate indicators such as temperature and mean sea-level pressure (MSLP). To do this analysis, temporal and spatial comparisons between high and low solar forcing are made. The simulated data is generated using the Max Planck Institute for Meteorology Earth System Model (MPI-ESM), in particular the ECHAM5 atmospheric model, with a nominal and a stronger solar forcing applied. This follows the methods in Jungclaus et al. (2010) [2], but in this study the primary focus is solar forcing. Throughout this paper an effort is made to link findings back to other contemporary research as well. The particular time periods of interest are the Medieval Climate Anomaly, from the mid 10th century to the mid 13th century, and the Little Ice Age, from the early 15th century until the mid 17th century. By focusing on these two anomalies, the hope is to find a conclusive link between solar radiation and said climate anomalies.

2 Background

2.1 Climate data proxies

Historic climate data over the past decades and even centuries is to some extent available, but studying long-term trends in the climate inevitably requires proxy data. A proxy is a piece of evidence that can be indirectly linked with some desired quantity to be studied. For example, tree ring width can be used as a proxy for precipitation in a certain area, since precipitation is one of the primary factors in promoting tree growth. Tree rings, and for example ice cores, are paleoclimate proxies, and can be used for many different studies. Historical records and eyewitness accounts also can be used [3]. Regarding solar forcing, there is a particular need for proxy data, since the majority of the periods of interest have no direct record of solar activity. This paper uses solar data which is reconstructed from cosmogenic isotope ^{14}C concentrations in tree rings [4].

2.2 Solar forcing

Solar forcing refers to the variation in solar radiation which is received by Earth. Relevant causes of variation in solar radiation can include sun spots, solar flares and the changing magnetic field strength of the star. Radiation is the primary source of the Earth's energy, and therefore fluctuations can affect the energy balance, and as such the climate of the Earth. However, there is still an active debate as to what extent solar forcing has an effect on cooling or warming.

2.3 Global and regional effects of solar forcing

While the greenhouse effect is one of the primary factors in climate variability and warming effects, solar forcing has some impact on variability, especially on intradecadal timescales. One contributor to this longer scale variability is the 11-year solar cycle, which was to some extent known since the late 18th century [3]. On a global scale, this has limited effect, although solar activity and temperature have been seen to coincide. This is best exemplified by the *Maunder Minimum* (MM) [2], a period between approximately $1645 - 1715$ A.D. which had an unusually low sun spot activity. The MM falls in a period known as the *Little Ice Age* (LIA), a period between $1400 - 1750$ A.D. which is characterized by a significant positive climate anomaly. However, like mentioned before, there remains debate around the correlation between the two phenomena, and whether there is any causal relationship. Recent studies seem to suggest that volcanic forcing, rather than solar forcing, would have been a greater contributor to the LIA [5].

2.4 Medieval Climate Anomaly and the Little Ice Age

Besides the Little Ice Age, there is also a historic period of significant climate variation between about 950 − 1250 A.D. known as the *Medieval Climate Anomaly* (MCA). Both of these periods have shown anomalous variability in previous studies, particularly in the Northern Hemisphere (NH). The MCA has a characteristic increase in temperature, whereas the LIA has been shown to have lower than usual temperatures. Various factors are thought to have played a role in these phenomena; solar forcing shows an increase and stark decrease in the MCA and LIA respectively. Additionally, volcanic forcing is thought to have played a role in the unusual temperatures of the LIA [5].

3 Method

3.1 Model data

The Medieval Climate Anomaly and the Little Ice Age have been correlated with solar forcing, however, recent studies show that the magnitude of solar forcing may have been overestimated in past studies [2, 6]. Thus, following the method of Jungclaus et al. [2], this paper will assess two different scenarios, one with higher and one with lower solar forcing, in order to see if over- or underestimating solar forcing can change the perspective on the MCA and LIA.

3.2 Ensemble construction

Two ensembles, with different Total Solar Irradiation (TSI) are compared in this study, and the same selection of model runs is used as in Jungclaus et al. [2]. This means E1, with 5 model runs, represents a nominal case, and E2, with 3 model runs, a scenario of increased TSI. These cases are made by estimation of the amplitude of the TSI based on the Maunder Minimum, and aligning with historical and previously estimated values for solar radiation. For details, see [2]. The TSI anomaly is then the difference with respect to a reference value of 1367 Wm^{-2}. Temperature and Mean Sea Level Pressure (MSLP) are extracted from the model runs of each ensemble. Then, the ensemble time series is computed using a bootstrapping method, where 1000 samples from all ensemble members, at each temperature recording. For MSLP, the ensemble members are averaged at each grid point. For both the temperature and MSLP ensemble, the time series are separated by season (winter and summer).

3.3 Data processing

The time slices are aligned with the solar forcing, such that all time series span the years 790−2005 A.D.. Then, a yearly mean is computed for all time series so that there are 1206 time slices, where each time slice is 96×48, representing grid points on the Northern Hemisphere (NH). For time series, the mean is taken over all grid points, and a 30-year moving average is applied in order to analyse the intradecadal trends in temperature variability. Processing and plotting has been done in MATLAB, where processing and plotting grid points on maps was done using reproduced and modified code from Sjolte et al. [7]. The Medieval Climate Anomaly (MCA) and Little Ice Age (LIA) are defined as 950 − 1250 A.D. and 1400 − 1750 A.D. respectively. In order to do spatial analysis, and in order to have a direct comparison between high and low solar forcing, $T_{MCA} - T_{LIA}$ is plotted for both ensembles. Likewise, the difference in mean sea level pressure $MSLP_{MCA} - MSLP_{LIA}$. What this will show is the maximum difference within one ensemble between low and high solar forcing. If there is a connection between solar forcing and these climate variables, some form of pattern ought to emerge on these anomaly plots.

3.4 Assumptions

In these methods, there is the implicit assumption of stationarity of the data. As such, non-linear relationships are not accounted for. An-

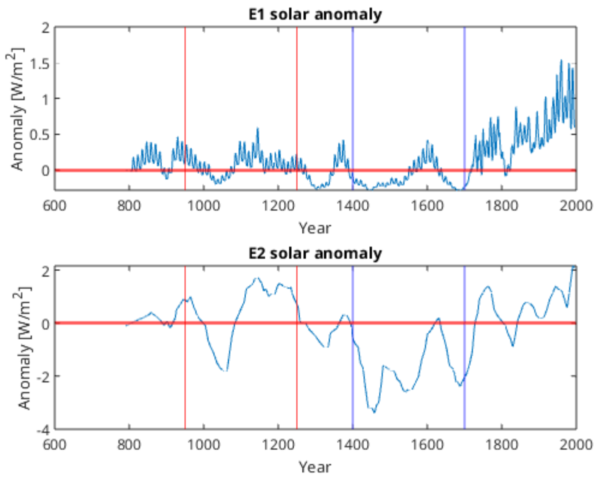

Figure 1: A visualization of the solar forcing anomaly in Wm^{-2}, with respect to a baseline level of 1367 Wm^{-2}. The E1 solar anomaly data is reconstructed from [6], whereas E2 solar anomaly is reconstructed from [2]. The vertical red and blue lines once again indicate the MCA and LIA respectively.

other assumption is that different climate forcings (volcanic, solar, anthropogenic) are linearly separable, meaning that it is assumed that the processes do not influence each other. Third, the model ensembles are assumed to contain diverse enough members for the analysis to be meaningful, that is, that not all ensemble methods are some statistical outliers. When it comes to defining reference periods, the values are taken directly from Jungclaus et al. (2010), in order to compare directly. It is assumed that these definitions of MCA, LIA and reference periods for temperature and solar activity are appropriate for this analysis.

4 Results

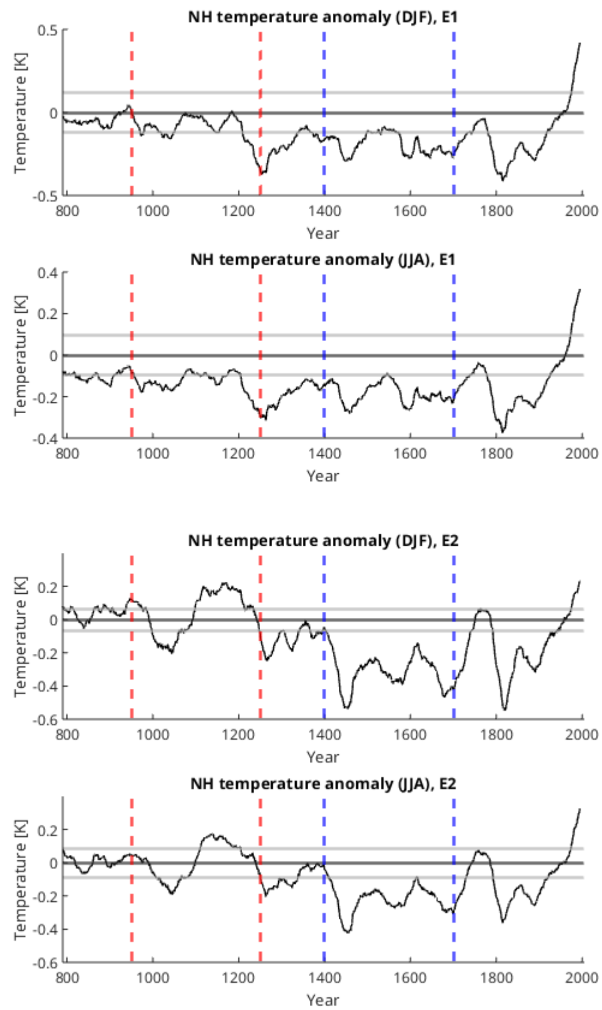

Figure 2: 30 year moving average of the temperature anomaly with respect to 1961 − 1990 A.D. baseline, for the entire simulation period of both ensembles. Plots are given for both DJF and JJA seasons. The horizontal black line represents the baseline, where the light grey lines are the standard deviation of the baseline. The red and blue dashed lines indicate the MCA and LIA respectively. The temperature is bootstrap sampled from the ensemble members before applying the moving average.

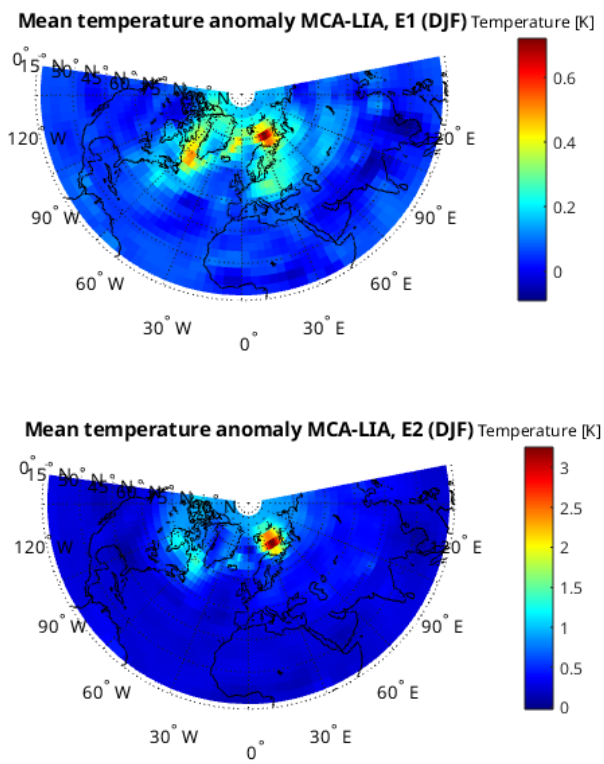

Figure 3: Spatial plots of the difference between mean temperature during the MCA and the LIA, for both ensembles. This difference is used to illustrate the maximum effect that solar forcing has in each ensemble. Each point on the heat map corresponds to the difference $T_{MCA} - T_{LIA}$ at that location. A positive value thus indicates that high solar forcing corresponds with a positive temperature anomaly compared to that same area during the LIA.

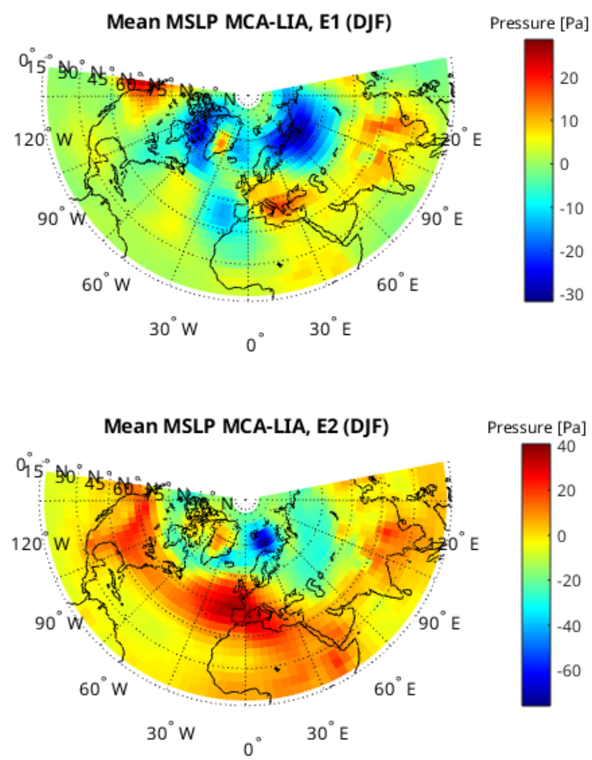

Figure 4: Spatial plots of the difference between MSLP during the MCA and the LIA, for both ensembles, determined in the same way as Figure 3. This difference is used to illustrate the maximum effect that solar forcing has in each ensemble. Each point on the heat map corresponds to the difference $T_{MCA} - T_{LIA}$ at that location. A positive value thus indicates that high solar forcing corresponds with a positive temperature anomaly compared to that same area during the LIA.

5 Discussion

Solar forcing The two different solar anomalies displayed in Figure 1 were determined by the same baseline reference value. Here it can be seen that the E2 ensemble indeed has a significantly stronger anomaly throughout the entire time series.

Time series analysis Firstly, to determine the difference between the ensembles in terms of climate variability, as a result of different forcing, the temperature time series for both ensembles (DJF and JJA) are plotted in Figure 2. In this figure, there is indeed anomalous signals for the MCA and LIA in the E2 ensemble (high solar forcing), with the clearest signal visible in the DJF period. There is no clear signal in the E1 time series.

Spatial temperature analysis For the spatial plots of both the temperature and MSLP, the decision was made to only analyse the patterns for December, January and February (DJF), due to the stronger variability in these winter months. This aligns with findings of e.g. Semenov et al. (2007) [8], that winter months show larger climate variability in the extratropical regions of the NH. However, summer (JJA) plots are available in Appendix A.

When it comes to the spatial patterns of the difference between MCA and LIA, there is an interesting pattern, where we see particularly see a positive difference in the extratropical region, indicating a higher than usual temperature during the MCA in winter. In both the E1 and E2, there is a very strong signal around the ice sheets of Svalbard, with moderate increase in temperature around the Greenland ice sheet as well.

What this shows is that a period of increased solar forcing (MCA) has increased temperature in the arctic region, compared to low solar forcing during the LIA. Since this region is largely covered by ice and snow during winter, it is plausible that positive feedback loops in the arctic system played a role here. With MCA constituting a significant temperature increase over base line, there may have been less ice sheet surface and more ocean that receives radiation. There is a strong albedo difference between these two surfaces, and as such, positive temperature increases result in a feedback loop where, as the ice sheet surface decreases, it does so at an increasing rate as the albedo of the overall arctic system decreases.

Spatial MSLP analysis Turning now to the mean sea level pressure, rather interesting patterns emerge. The difference between MCA and LIA in terms of MSLP shows stronger, more extreme pressure differences during high solar activity. Lower pressure is seen across most of the arctic and Northern Europe, while southern Europe and the Americas show higher pressure. These pressures are amplified in the E2 ensemble. What is interesting to note is that the pressure pattern is very much reminiscent of the North Atlantic Oscillation, that is, the pressure difference between Iceland and the Azores. In the results of Figure 4, the difference between MCA and LIA seems to indicate that high solar activity coincided with a positive NAO phase during the MCA. This agrees with findings that has been found in other studies, e.g. see [9]. Since positive NAO contributes generally to warming of the NH, this is an additional factor that may explain the MCA.

6 Conclusion and outlook

Overall, the findings in this study are in line with Jungclaus et al.. In said paper, the authors concluded that volcanic activity during the LIA likely had a bigger influence on the difference between MCA and LIA anomalies than solar forcing. The time series of the E2 ensemble show that there is certainly some correlation between the solar activity and temperature. However, there is no clear causal relationship. Spatial analysis provides another perspective, but since the MCA coincided with a positive NAO phase, and the LIA with global cooling due to volcanic activity, there is not enough conclusive evidence to suggest that solar forcing is primarily, or directly at all, responsible for the MCA and LIA anomalies. In order to definitively say whether solar forcing was a primary cause of these anomalies, further studies should compare between the timings of volcanic activity and solar activity. Additionally, higher resolution or more accurately calibrated solar forcing reconstructions could help in answering this question.

References

[1] Bas Van Geel et al. "The role of solar forcing upon climate change". In: *Quaternary Science Reviews* 18.3 (1999), pp. 331–338.

[2] Johann H Jungclaus et al. "Climate and carbon-cycle variability over the last millennium". In: *Climate of the Past* 6.5 (2010), pp. 723–737.

[3] Christoffer Karoff et al. "Christian Horrebow's sunspot observations–II. Construction of a record of sunspot positions". In: *Solar Physics* 294 (2019), pp. 1–16.

[4] Sami K Solanki et al. "Unusual activity of the Sun during recent decades compared to the previous 11,000 years". In: *Nature* 431.7012 (2004), pp. 1084–1087.

[5] Mathew J Owens et al. "The Maunder minimum and the Little Ice Age: an update from recent reconstructions and climate simulations". In: *Journal of Space Weather and Space Climate* 7 (2017), A33.

[6] NA Krivova, LEA Vieira, and SK Solanki. "Reconstruction of solar spectral irradiance since the Maunder minimum". In: *Journal of Geophysical Research: Space Physics* 115.A12 (2010).

[7] Jesper Sjolte. *BERN03 Introduction to Modelling of the Climate System, Exercise 1-4.*

[8] VA Semenov. "Structure of temperature variability in the high latitudes of the Northern Hemisphere". In: *Izvestiya, Atmospheric and Oceanic Physics* 43.6 (2007), pp. 687–695.

[9] Valérie Trouet et al. "Persistent positive North Atlantic Oscillation mode dominated the medieval climate anomaly". In: *science* 324.5923 (2009), pp. 78–80.

A Additional plots

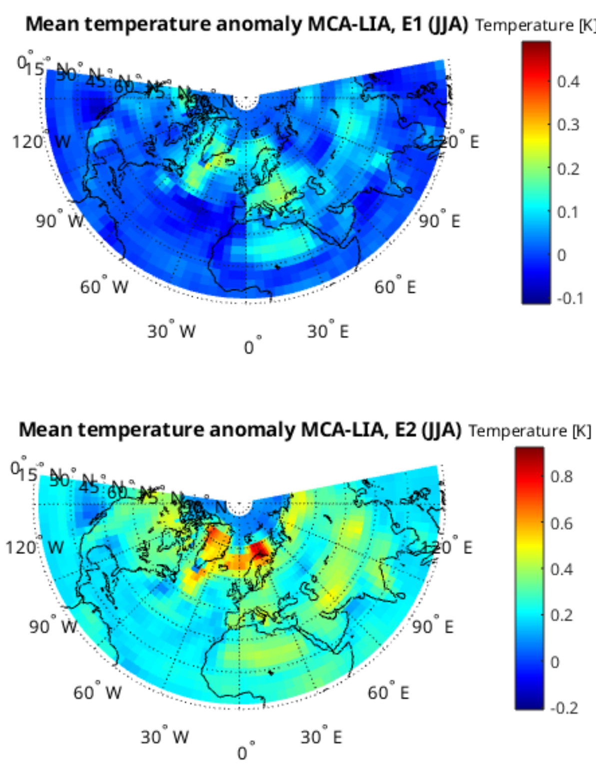

Figure 5: Spatial plots of the difference between mean temperature during the MCA and the LIA, for both ensembles. This difference is used to illustrate the maximum effect that solar forcing has in each ensemble. Each point on the heat map corresponds to the difference $T_{MCA} - T_{LIA}$ at that location. A positive value thus indicates that high solar forcing corresponds with a positive temperature anomaly compared to that same area during the LIA.

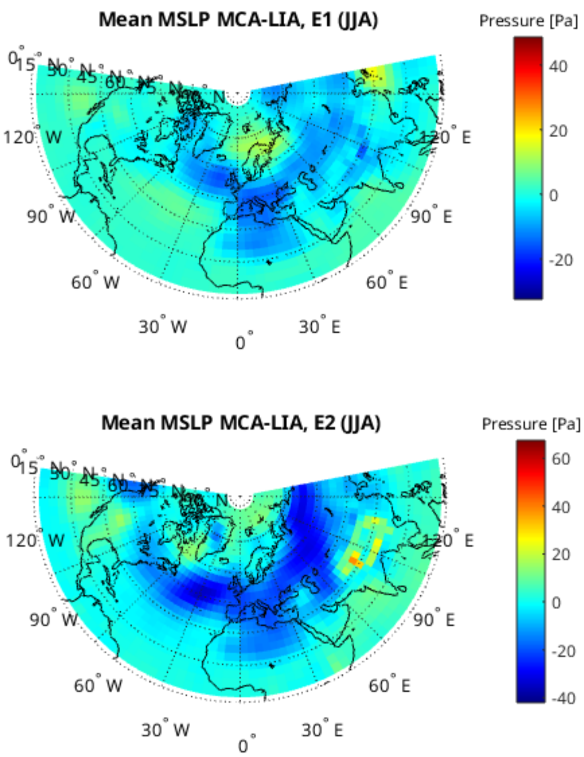

Figure 6: Spatial plots of the difference between MSLP during the MCA and the LIA, for both ensembles, determined in the same way as Figure 3. This difference is used to illustrate the maximum effect that solar forcing has in each ensemble. Each point on the heat map corresponds to the difference $T_{MCA} - T_{LIA}$ at that location. A positive value thus indicates that high solar forcing corresponds with a positive temperature anomaly compared to that same area during the LIA.