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Solar influence on climate during the past millennium: results from transient simulations with the NCAR Climate System Model

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Abstract

Changes in solar activity likely explain a considerable part of global climatic variation over the past millennium. Because solar variability prior to the satellite period must be scaled from proxy data, large uncertainty exists over the low-frequency magnitude of the forcing. We forced a coupled climate system model over the published range of solar irradiance estimates to determine if part of the previously estimated large range of past solar irradiance changes could be excluded. Transient simulations integrated from AD 850 through the ’Medieval Warm Period’ and the ‘Little Ice Age’ to the present show a clearly detectable signal from the sun as well as from volcanic aerosols. The temperature response is larger over land and in high latitudes resulting in a larger temperature response in the Northern than in the Southern hemisphere. Solar forcing produced low-frequency climate evolution generally consistent with the data-based temperature reconstructions. The largest peak-to-peak temperature differences are found with largest solar forcing. Smaller rather than larger long-term trends in solar irradiance appear more likely and produced modeled climates in better agreement with the range of Northern Hemisphere temperature proxy records both in phase and magnitude. Despite the significant sensitivity of the model to solar forcing, even large solar combined with realistic volcanic forcing could not explain the 20th Century warming without greenhouse gas effects. Although solar and volcanic effects appear to dominate most of the slow climate variations within the past thousand years, greenhouse gas effects have dominated the last century.
1. Introduction

Understanding and quantifying natural climate variability on decadal to centennial time scales is a prerequisite to projecting future climate changes. It is important to evaluate comprehensive models in the pre-industrial period when natural variations were (relatively) pronounced and anthropogenic influences were comparatively small. The recently improved records of the variations in climate of the past 1000 years (1) together with solar and volcanic forcing histories (2, 3) provide a key opportunity for (a) evaluating long transient simulations with Atmosphere-Ocean General Circulation Models (AOGCMs) over the preindustrial era, (b) for exploring the proposed magnitudes of past solar irradiance changes and (c) to estimate natural contributions to century scale climate variability.

A range of Northern Hemisphere (NH) and one global surface temperature reconstructions for the past millennium have become available in the past few years. These studies infer the magnitude of past temperature variations from proxy data such as tree ring width and density, coral growth, ice core, speleothem and documentary data or from borehole temperature profiles. The reconstructions have a variety of uncertainties and, especially at longer time scales, individual temperature series deviate notably from each other. This is particularly the case for the magnitude of the cooling during the period generally referred to as the Little Ice Age (~1300-1850). However, most maintain a similar temporal structure, and taken together they suggest that natural century scale NH-temperature variations over the past millennium remained within 0.3°C (low estimate: (4, 5) to about 0.9°C (high estimate, e.g., (6-8)).
The dominating natural forcings on sub-millennium time scales result from explosive volcanism and from changes in solar energy output. Great uncertainty remains about their magnitude. Explosive volcanic eruptions generate large aerosol clouds in the stratosphere where they perturb both incoming and outgoing radiation (9, 10). Generally, the former is the dominating effect and surface cooling occurs (11, 12). The bulk of the direct forcing for individual events is limited to a few years by the relatively short residence time of the injected particles in the lower stratosphere (13). Prolonged effects have been documented for temporally relatively closely spaced eruptions (14, 15), but could also result from extremely large eruptions with injection of material at very high altitudes.

There is an ongoing debate on the role of the sun in recent observed warming. Century-scale solar irradiance variations have been proposed as cause for past climatic changes (e.g. (16, 17)). The latest summaries of the various uncertainties can be found in two recent reviews (18, 19). Satellite data since 1979 quantify the irradiance variations associated with the 11-year Schwabe sunspot cycle to roughly 0.08-0.1% of the ~1367 Wm\(^{-2}\) solar radiation reaching the top of our atmosphere (19). This variation translates into a radiative forcing of about 0.2-0.3 W m\(^{-2}\), roughly a factor of 10 smaller than the radiative forcing by well-mixed Greenhouse Gases of 2.4 W m\(^{-2}\) in 2000 AD (relative to 1750 AD). Although direct measurements of solar irradiance are limited to the satellite period (19), tentative correlations with records of sunspots (20, 21), aurora histories, geomagnetic indices, or the production rates of cosmogenic nuclei such as 10-Beryllium (\(^{10}\)Be) and radiocarbon (\(^{14}\)C) (2, 22) in conjunction with magnetic behavior of solar-like stars (23, 24) have been used to estimate solar irradiance in the past. The temporal
evolution of the different proxy series, particular in certain well-defined frequencies
(\sim11\text{-}year \textit{Schwabe Cycle}, \sim80\text{-}85\text{-}year \textit{Gleissberg Cycle}, \text{and} \sim207\text{-}year \textit{deVries Cycle}),
is in reasonable agreement across most solar proxies (18). However, the scaling required
to translate a proxy record of sunspot number or production rate of \(^{10}\text{Be}\) into actual solar
irradiance anomalies is highly uncertain and published estimates of multi-decadal solar
irradiance changes vary by a factor of more than five ((2, 14).

Possible transient effects of solar irradiance changes on climate have been
investigated with computationally efficient models, such as Energy Balance Models (14,
25) and Models of Intermediate Complexity (26, 27) as well as with Atmosphere-Ocean-
General Circulation Models for the 20\textsuperscript{th} century (28) and the past (29).

Here, we employ a coupled AOGCM in experiments covering the period of the
last 1150 years. The low-frequency solar forcing was taken from the \(^{10}\text{Be}\) record and
scaled to solar irradiance over much of the published range. We identify links between
the solar forcing and modeled temperature as well as proxy-based temperature
reconstructions.

2. Model and Forcings

Simulations for this study are conducted with the NCAR Climate System Model
(CSM), Version 1.4, a global coupled atmosphere-ocean-sea ice-land surface model
without flux adjustments (30, 31). The atmospheric model is CCM3, a spectral model
with 18 levels in the vertical. For these experiments, it is run at T31 resolution (an
equivalent grid spacing of roughly 3.75 by 3.75 degrees). The land surface model has
specified vegetation types and a comprehensive treatment of surface processes. The land
model uses the same grid spacing as the atmosphere model. Freshwater balance is maintained with the precipitation scaling scheme described in (32). The ocean model is the NCAR CSM Ocean Model (NCOM) with 25 levels, 3.6° longitudinal grid spacing, and latitudinal spacing of 1.8° poleward of 30° smoothly decreasing to 0.9° within 10° of the equator. The sea ice model includes ice thermodynamics based on the three-layer model and ice dynamics based on the cavitating fluid rheology. The grid spacing is the same as that of the ocean model.

The model was forced using observation-based time histories of solar irradiance, spatially explicit aerosol loading from explosive volcanism, the greenhouse gases CO₂, CH₄, N₂O CFC-11 and CFC-12, and anthropogenic sulfate aerosols (Figure 1). Orbital parameters are kept constant at 1550 conditions and natural levels of sulfate aerosols in the troposphere are prescribed with a recurring annual cycle.

Different estimates of past solar irradiance changes in the NCAR CSM are applied by scaling a recent ¹⁰Be history (2) over the past 1150 years using three very different estimates of the scale factor (Figure 1). For two full-length (1150-years) simulations solar irradiance was scaled to a reduction during the Maunder Minimum (AD 1645-1715) of 0.25% (21) and 0.65% (33) relative to present, representing a ‘medium’ and a ‘high’ case. Additionally, we performed a 450-year simulation from AD 1550 to 2000 applying a Maunder Minimum reduction scaling of 0.1% (34). This, for reasons of computational resource availability, shorter, ‘low’ solar forcing simulation addresses recently raised doubts on the existence of any additional low-frequency trend in solar irradiance beyond the instrumentally measured variations of the 11-year cycle (24, 35).
The volcanic forcing was established following earlier work (15) by converting ice core aerosol proxies to latitudinal and temporally varying atmospheric aerosol fields. Volcanic aerosol was specified as a single aerosol size distribution and optical depth is scaled linearly with the aerosol loading. Atmospheric CO$_2$, CH$_4$ and N$_2$O concentrations were individually prescribed following ice core measurements and direct atmospheric observations. The CFC-11, scaled to take into account the radiative forcing by other halogenated species and SF$_6$ (36), and CFC-12 concentration histories are based on historic emission data and recent measurements. The volcanic and anthropogenic forcing histories were the same in all three simulations. A parallel control experiment without any forcing changes was run over 1150 years. This control exhibits a drift in global-average surface temperature of 0.07ºC per century over the first 600 years; after 1500 AD global average surface temperature remains approximately constant. All results shown here are detrended; shown are the residuals after subtracting a spline fit for individual months of the annual cycle at each model grid point obtained from the control integration.

The main experiments include the anthropogenic change in radiative forcing over the industrial period. In order to evaluate the contribution of natural forcing (solar and volcanic) to the 20th century climate change additional simulations were performed over the period 1870 to 1999 with all anthropogenically influenced forcings fixed at the 1870 AD values. These simulations are branches of the three main experiments to take into account the inertia of the climate system and the influence of preindustrial forcing changes on 20th century climate.
3. Results

Both simulations covering the full 1150-years (Figure 2) show a clear two-stage initial warming interrupted by a temperature drop in the 11th century. Relative maxima in global temperatures occur during the 10th century and between the late 11th and the 12th century. Subsequently, modeled temperatures decrease. Globally, the coldest episodes are in the 15th (high solar forcing), 15th and 17th century (medium solar forcing) and the 19th century (low solar forcing, but based on a shorter run). Over the instrumental record after 1850, all three runs are essentially indistinguishable and they closely match the observed global warming both in magnitude and in temporal evolution. In all three simulations, decadal-mean global average surface temperature was higher during the most recent three to four decades than during the previous 1100 years. During the preindustrial period, the three experiments are generally separated by several tenths of a degree Celsius (Figure 2). The difference is due to the solar forcing since that was the only difference between the experiments. This difference is greater than one standard deviation of the low-frequency variability of the control run of 0.107°C. Decadal-scale Northern Hemisphere surface temperature is generally synchronous with the global-mean, but NH-perturbation amplitudes are larger by about 20%.

Several sharp cooling episodes mark the response to very large volcanic forcing (e.g., AD 1258, 1453, 1815). The largest volcanic forcing was estimated for AD 1258 (Figure 1) following the probably largest explosive eruption of the past few thousand years. The source volcano of this event is still unknown, although from deposition starting ~1258 at both polar ice caps it is clear that it is a tropical event. This particularly large event is followed by a remarkable sequence of large eruptions causing a clear
temperature decrease of several tenths of a degree Celsius over the late 13th century (Figure 2). Similar cumulative volcanic cooling is also simulated in the mid 15th, the 17th, the early 19th as well as (to a lesser degree) late 19th - early 20th century.

The pre-industrial range in multi-decadal global surface temperature is reduced by more than a factor of two in the low and medium experiments compared to the high solar forcing case (Figure 2). The amplitude difference between the warmest and coldest periods at the decadal time scale is ~0.4°C (pre-1850) for the low and medium simulations as compared to ~1°C for the high scaling. The largest scaling of the solar forcing yields both the coldest and warmest decades in all simulations prior to the late 20th century.

There is a link between simulated low-frequency climate variability and the natural climate forcings during the preindustrial period. The correlation between solar forcing and modeled global surface temperature series decreases with diminishing solar forcing magnitude. Fifty-year long, Gaussian-weighted global surface temperature variations in the large-forcing experiment is almost entirely determined by the solar forcing (decadal data : $r^2=0.88$). This cause-effect link is reflected in a tight phase relationship in the dominant century-scale frequency band of solar variability (~1/200 yr, Supplemental Material, Figure SUP-1). The strength of the relationship between solar forcing and global surface temperature ($r^2=0.47$) as well as the magnitude of the response are reduced in the medium-forcing run. The solar forcing response becomes smaller relative to the model’s internal variability and the ratio of solar signal to volcanic influence and/or model noise decreases. Deviations of simulated temperature evolution
from the evolution of irradiance do occur repeatedly and are almost exclusively negative due to explosive volcanism. (Supplemental Material, Figure SUP-1).

The simulated decadal-scale NH temperature variations of the medium-scaled run fall mostly within the uncertainty band from the proxy-based reconstructions (Figure 3b). Only during the cool interval within the ‘Medieval Warm Period’ (~1050 AD) are the temperatures falling below this range. Generally, the reconstructed high temperatures in the 11th and 12th centuries and the cold conditions between 1450 and 1800 AD are reflected in the model results. Relative minima and maxima found in the proxy reconstructions such as those in the late 18th century and the beginning of the 19th century or around 1570 and 1450 are also found in the medium-scaled simulation. For a comparison between modeled NH temperatures with various proxy reconstructions see supplemental material, Figure SUP-2.

The results of the low and high solar forcing experiments encompass the (pre-1850) amplitude range in multi-decadal-averaged NH temperatures of the available proxy reconstructions. The preindustrial amplitude of up to 1.2°C for NH-temperature found in the high solar forcing simulation is larger than in all reconstructions. However, the variations of the order of 0.9°C proposed by (7, 8) are similar. The pre-1850 NH-temperature range of 0.3°C found in the low case is essentially the same as proposed by (5).

Solar forcing and low-frequency volcanic forcing are anticorrelated around 1600 (Figure 1). The 10Be and radiocarbon records (2, 18) suggest that solar forcing increases in the late 16th century to peak early in the 17th century, whereas volcanic eruptions tend to cool the Earth surface at the same time. It is a robust features of all temporally-
resolved reconstructions that the NH cools after ~1570 AD (Figure 1a). This is also the case in the medium-scaled run (Figures 2 and 3). In contrast, simulated NH temperature in the large-scaled run continues to increase after 1570 until the peak in the $^{10}$Be solar forcing around 1620 AD. This suggests that the ratio between prescribed solar forcing and volcanic forcing is too big in the large-scaled run. This effect of a very strong solar influence on the phase of the low-frequency variation is also illustrated in the supplemental material (Figure SUP-1b).

Turning to the instrumental record, all three simulations with anthropogenic forcing yield a twenty-century warming of about 0.5ºC (small and high solar) to 0.7ºC (medium solar) (Figure 3c). This is fully consistent with the data-based estimate of 0.6+-0.2ºC and the evolution of global-mean surface temperature very closely matches the instrumental record. The natural-only extensions for all three simulations after 1870 (holding greenhouse gases and tropospheric aerosol constant at 1870 conditions) yield a 20th century peak warming (decadally smoothed data) of about 0.2ºC which is reduced to 0.1ºC by the end of the century through increased volcanism. The separation of a human-induced warming from the natural background temperature evolution occurs early in the 20th century in the model.

Figure 4 shows the spatial pattern of regression coefficients for the relationship between solar forcing and temperature response. The patterns, while not a validation of the model, do show realistic features, suggesting that in broad terms the model correctly captures the spatial impact of solar-induced temperature changes. The most prominent feature is the tendency to have more sensitivity (larger regression coefficients) over land than over the oceans, as expected due to the higher heat-absorbing capacity of the oceans.
The model result also exhibits polar amplification, or higher sensitivity at high latitudes, with a greater effect in the NH because of the interaction of this effect with the land-ocean contrast. The southern Hemisphere with its sparser land masses shows less amplification. There is some variability in sensitivity within the NH high latitude regions, likely because of persistent climate patterns associated with planetary wave structure. Finally, there are some regions with negative relationships to solar forcing, mainly in the NH high latitude oceans. These may represent regions of complex interactions between climate, ocean currents and ocean heat uptake, possibly associated with a known internal model oscillation, but they also occur in areas with significant sea ice. The model is known to have systematic biases in its simulated sea ice, so the regressions in these regions could be exaggerated or in error.

4. Discussion and Conclusions

A set of transient millennium-long simulations with the NCAR CSM1.4 coupled atmosphere-ocean-land-sea ice general circulation model has been performed to address the links between solar forcing and surface temperature change. The NCAR CSM1.4 has a low climate sensitivity (\(\sim 2^\circ\text{C} \) for a doubling of atmospheric CO\(_2\)) and correspondingly simulated responses to solar and other forcings are near the lower end of the range spanned by the current suite of AOGCMs. The model has been forced by solar irradiance changes and stratospheric sulfate aerosol concentrations from explosive volcanic eruptions as well as with the known atmospheric history of the anthropogenically influenced greenhouse gases and anthropogenic sulfur dioxide emissions into the troposphere. The solar irradiance evolution has been prescribed following the South Pole
The $^{10}$Be record has been linearly scaled to a Maunder Minimum solar irradiance reduction of 0.65% (high case), 0.25% (medium case) and 0.1% (low case) relative to today (2). In this way, the uncertainty range associated with a possible long-term trend in solar irradiance is covered by the simulations. Uncertainties arising from a potentially non-linear relationship between $^{10}$Be concentration in ice, its production rate, and solar irradiance (18) are not addressed here. These are thought to be of less importance compared to the scaling uncertainty. Spatially explicit forcing from explosive volcanism has been constructed from ice core proxies and assuming a single sulfate particle size distribution independent of the magnitude of the events (15). Reconstructed forcing appears too high for the largest eruptions (e.g. 1258 AD or 1815AD), with simulated temperature depressions larger than reconstructed, possibly because the real particle distribution might have been shifted to larger particles (with less effective backscattering properties) for those large events. Other damping mechanisms might exist (37). The modeled (decadal-scale) NH surface temperature for the medium-scaled experiment falls within the uncertainty range of the available temperature proxy reconstructions and the main features of the proxy records are reproduced. A clear link between the $^{10}$Be solar proxy and simulated NH temperatures has been identified. Local minima and maxima found in the proxy NH temperature reconstructions are also evident in the simulations. A planetary wave response to solar forcing has been identified similar as in earlier AOGCM studies (11, 38).

The temperature proxy records suggest that the ensemble obtained by combining the NCAR CSM with its low climate sensitivity and three different natural forcing histories, very likely encompass the realistic range of naturally-forced low frequency NH-
temperature variations during the past 1150 years. This conclusion holds irrespective whether in reality the temperature variations were caused by irradiance changes and volcanic eruptions alone or in combination with indirect solar mechanisms, such as solar-induced changes in stratospheric ozone and wave dynamics or cloud properties. The high solar forcing appears incompatible with the phase relationships and magnitude between reconstructed and simulated temperatures in the dominant solar frequency band of around 1/200 years and the reconstructed cooling around 1570 appears too late in the large-scaled simulations in response to strong solar forcing. Thus, given the low (~2°C) climate sensitivity of the CSM a large (0.65%) solar irradiance change appears unlikely, though not impossible. However, smaller, and possibly much smaller irradiance changes are more consistent with most of the available temperature reconstructions both in magnitude and phase.

The 20th century warming found in the instrumental record is clearly reproduced and very similar between the three experiments with anthropogenic greenhouse gas forcing and sulfate emissions included. On the other hand, the simulations with only natural forcings included yield a 20th century peak warming of about 0.2 °C which is reduced to 0.1°C by the end of the century through increased volcanism. This suggests that a rebound from cooler preindustrial conditions plays a minor role for the 20th century warming. In conclusion, the range of NH-temperature reconstructions and the cosmogenic isotope record as a proxy for solar forcing together with volcanic forcing constrain the natural contribution to the 20th century warming to be less than 0.2°C. Anthropogenic forcing must account for the difference between a small natural temperature signal and the observed warming in the late 20th century.
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References

Figure Captions

Figure 1

Prescribed forcings. Volcanic forcing (15) is indicated as visible optical depth (top). Solar forcing is obtained by scaling $^{10}$Be data of (2) to a Maunder Minimum reduction in solar irradiance relative to today of 0.1% (green dash-dot, low solar simulation from 1550 to 2000 AD), 0.25% (red, solid, medium solar simulation from 850 to 2000 AD) and 0.65% (blue, dash, high solar simulation from 850 to 2000 AD). The 11-year solar cycle is not included in the forcing. Anthropogenic SO$_2$ emissions (dash-dot) and forcing by greenhouse gases (bottom, solid), expressed as CO$_2$ equivalent are from (36). The atmospheric CO$_2$ concentration is shown by the black, dashed line. In addition to three long simulations with prescribed solar and identical volcanic and greenhouse gas forcings and SO$_2$ emissions, three ‘natural-only’ simulations were branched-off from the high, medium, and low solar simulations at year 1870 with greenhouse gas concentrations and SO$_2$ emissions kept at year 1870 level (green lines).

Figure 2

a) Global average surface temperature (50-year Gaussian weighted average) simulated with the Paleo-NCAR CSM 1.4 with prescribed high (blue), medium (red) and low (green) solar forcing. Annual data are shown for the medium solar forcing run (red, thin line) and for the instrumental record of global average surface temperature (black). Volcanic and greenhouse gas forcing and SO$_2$ emissions are the same in all three simulations. Ranges depict two positive and negative standard deviations (sdv) around
the 50-year averages computed from 1000 years of an unforced control simulation (sdv = 0.107°C).

**Figure 3**

a) Reconstructed NH average surface temperature anomalies over the past millennium (5, 7, 8, 39-42). All series are as published originally and no additional scaling has been performed, but annual records have been smoothed with a fifty-year long Gaussian filter.

b) Northern Hemisphere surface temperature from the medium-scaled (red) solar forcing simulations versus proxy-based reconstructions (gray). The grey range is spanned by the NH reconstruction of (5) (dash), and of (8) (dash-dot). Reconstructions from (7) are indicated by the maron line and from (40) by the solid, black line. All data were smoothed with a cut-off period of 30 years.

c) Simulated versus the instrumental record of global average surface temperature (black, thick solid line). Decadally-smoothed (10-yr averages) results from the high (blue), medium (red), and low (green) solar forcing experiments with (solid) and without (dashed) anthropogenic forcings are shown together with the annual results of the medium experiments (thin, red solid line).

**Figure 4**

The spatial pattern of solar-induced temperature changes in °C per W m$^{-2}$ for the high solar forcing simulation over the period from AD 1000 to 1850. Values are calculated for
each grid-point as the slope of the linear correlation between solar irradiance anomalies and local temperature, both filtered with a 200-year frequency window using wavelet analysis. Global mean response is equivalent to 0.05 °C for each W m² irradiance change at the top of the atmosphere.
Figure SUP-1

a) Comparison of 50-year Gaussian-weighted global temperature anomalies (solid) and prescribed solar irradiance changes (black, dash) for the high (blue), medium (red), and low (green) solar forcing simulations. Volcanic forcing is expressed as change in visible optical depth (VOD) (bottom) and gray bars indicate periods of particular strong volcanic forcing. Temperature scale of 0.5°C is shown on the right, solar irradiance scale of 10 W m⁻² on the left. The ranges of prescribed solar irradiance anomalies are indicated by dashed arrows on the left. The differences in simulated global mean temperature for year 2000 AD between the high, medium and low solar forcing simulations and the corresponding natural forcing only simulations is indicated by the arrows on the right. The transient results of the natural forcing only simulations are shown for the high solar case (green). The instrumental record of global average surface temperature is given by thin, green lines.

b) ~200-year band from a discrete wavelet decomposition (43) for the solar irradiance record (black, based on the medium-scaled record, but the temporal structure is the same for the others) and simulated global average surface temperature from the three long simulations (control: cyan; medium solar: red; and high solar: blue). The magnitudes are directly comparable between the model runs indicating increased amplitude of climate response with increased forcing.

Figure SUP-2

a) Reconstructed NH surface temperature anomalies as published by Jones et al. (39) (annual mean; green), Mann and Jones (5) (30-yr Gaussian filter; blue), Crowley...
and Lowery (14) updated by Crowley et al. (44) (11-yr running averages, 30°N to 90°N, magenta) and Esper and co-workers (7) (annual mean, dark green). The reconstructions are compared with the medium solar forcing simulation (red, NH-average or NH extratropics); smooth trends were obtained by applying a 50-year Gaussian filter or 11-yr running averages. The small solar experiment (1550-2000, green) is also shown in comparison with (5). The instrumental record is given by the black line.
Figure 1
Figure 2
Figure 3
Figure 4

Regression Surface Temperature to Solar Forcing

D0-D4 Period 1000-1850

90N 60N 30N 0 30S 60S 90S

180 150W 120W 90W 60W 30W 0 30E 60E 90E 120E 150E 180

-0.25 -0.15 -0.05 0.05 0.15 0.25
Suplemental Material Figure SUP-1
Supplemental Material, Figure SUP-2