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On the effect of a new grand minimum of solar activity on the future climate on Earth

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[1] The current exceptionally long minimum of solar activity has led to the suggestion that the Sun might experience a new grand minimum in the next decades, a prolonged period of low activity similar to the Maunder minimum in the late 17th century. The Maunder minimum is connected to the Little Ice Age, a time of markedly lower temperatures, in particular in the Northern hemisphere. Here we use a coupled climate model to explore the effect of a 21st-century grand minimum on future global temperatures, finding a moderate temperature offset of no more than −0.3°C in the year 2100 relative to a scenario with solar activity similar to recent decades. This temperature decrease is much smaller than the warming expected from anthropogenic greenhouse gas emissions by the end of the century. **Citation:** Feulner, G., and S. Rahmstorf (2010), On the effect of a new grand minimum of solar activity on the future climate on Earth, *Geophys. Res. Lett.*, *37*, L05707, doi:10.1029/2010GL042710.

1. Introduction

[2] The Sun, the dominant source of energy for Earth's climate system, shows a rich spectrum of variations on a wide range of timescales, for the most part originating from changes in the Sun's magnetic field [*Weiss and Tobias*, 2000]. One of the most prominent manifestations of solar variability are sunspots, dark regions visible on the solar disk, which show a regular pattern of maxima and minima with a period of about 11 years. This cycle is often called the Schwabe cycle and is part of a 22-year magnetic cycle termed the Hale cycle. Sunspot observations enable scientists to trace these variations back to the first telescopic observations starting in 1610, and solar activity over the last four centuries is indeed mostly characterised by periodic 11-year variations.

[3] In the past, however, this regular 11-year cycle was interrupted several times by grand minima of solar activity, usually lasting for several decades. During the time from about 1645 to 1715, for example, the Sun experienced a period of low activity called the Maunder Minimum (MM), and its surface showed only very few sunspots [*Eddy*, 1976]. Variations of sunspot number go hand in hand with changes of solar luminosity (especially in the ultraviolet) and of the solar wind, an magnetised outflux of charged particles from the Sun, effects which can, in principle, affect the climate on Earth.

[4] The changes associated with solar variability are small, however, and the influence of solar activity on the Earth's climate remains a controversial topic with many open questions [*Lean*, 1997; *Foukal et al.*, 2006]. Although their contribution to recent warming is negligible [*Lean and Rind*, 2008; *Lockwood*, 2008], there is evidence for contributions to temperature variability both from the 11-year cycle [e.g., *Lean and Rind*, 2008] and from grand minima in the past. Indeed, the MM coincides with a portion of the "Little Ice Age," a period of markedly lower temperatures over large parts of the globe [*Mann et al.*, 2009].

[5] The extraordinary length of the present minimum of solar activity during the Sun's 11-year cycle led to the suggestion that the Sun might enter a new prolonged period of low activity similar to the MM [*Livingston and Penn*, 2009]. Independently, forecasts for future solar activity based on statistical characteristics of solar cycles and the non-linear physics of the solar dynamo generating the magnetic field suggest an end of the 20th century grand maximum and a transition to lower solar activities, followed by a grand minimum at the end of the 21st century [*de Jager and Duhau*, 2009].

[6] The expected climatic effects of a new grand minimum of solar activity during the 21st century have been widely discussed both among scientists and in the broader public, but no detailed studies were available in the scientific literature. Recently, *Song et al.* [2010] published results from idealised equilibrium simulations of a new grand minimum for the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) B1 scenario Here we use a fully coupled climate model to study the influence of a new MM during the 21st century on future global temperatures under continuing anthropogenic forcing following the IPCC SRES A1B and A2 scenarios.

2. Model Experiments

2.1. Model Description

[7] The simulations have been performed with the coupled climate model of intermediate complexity CLIMBER-3α [*Montoya et al.*, 2006]. CLIMBER-3α consists of an ocean general circulation model [*Pacanowski and Griffies*, 1999] with a resolution of 3.75° × 3.75° and 24 layers coupled to a 2.5-dimensional statistical-dynamical atmosphere [*Petoukhov et al.*, 2000] (resolution of 22.5° in longitude and 7.5° in latitude; 16 vertical layers) as well as models for the land surface interaction including vegetation [*Petoukhov et al.*, 2000] and sea ice [*Fichefet and Morales Maqueda*, 1997]. In CLIMBER-3α, the equilibrium climate sensitivity to a doubling of the atmospheric CO_2 concentration is 3.4° (A. Levermann, private communication, 2010).

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Table 1. Comparison of Averaged Modeled Global Mean Temperature Anomalies Relative to 1961–1990 for Four Past Grand Minima With Reconstructed Values for the Two Solar Activity Scenarios With Total Solar Irradiance, TSI, of the Maunder Minimum 0.08% and 0.25% Below Its Value in 1950, Respectively

			Model	
Minimum	Period	Reconstruction (°C)	TSI(1 − 0.08%) (°C)	TSI(1 − 0.25%) (°C)
Wolf	1280–1350	−0.32	−0.36	−0.44
Spörer	1450–1550	−0.46	−0.42	−0.65
Maunder	1645–1715	−0.47	−0.49	−0.68
Dalton	1790–1830	−0.42	−0.45	−0.51

2.2. Millennium Simulations

[8] The 21st-century simulations described below continue runs over the past millennium published in *Jansen et al.* [2007], where they are compared to a range of climate models (both general circulation models and intermediate complexity models) and northern-hemisphere temperature reconstructions, showing very good general agreement.

[9] Climate forcings for these millennium simulations were taken from *Crowley* [2000] for the volcanic forcing, from the compilation by *Jansen et al.* [2007] for pre-industrial greenhouse gas concentrations, and from *Joos et al.* [2001] for carbon dioxide and other anthropogenic constituents since the beginning of the industrialised era. Two different reconstructions for the total solar irradiance (TSI) were used. One is based on ^{10}Be isotope measurements from an ice core [*Bard et al.*, 2000] and is scaled to a 0.25% reduction of TSI during the MM relative to the TSI in the year 1950 of 1366 W/m^2 [*Jansen et al.*, 2007], while the other infers TSI from a model of the Sun's magnetic flux [*Wang et al.*, 2005] after 1713 and uses *Bard et al.*'s [2000] TSI scaled to a 0.08% reduction in MM TSI relative to 1950 for earlier epochs [*Jansen et al.*, 2007]. This higher value of the TSI during the MM agrees well with recent TSI reconstructions [*Steinhilber et al.*, 2009].

2.3. Twenty-First Century Simulations

[10] To investigate the influence of a new grand minimum of solar activity during the 21st century on future climate, scenarios for the evolution of the various climate forcings until 2100 are required. These future forcings were set up as follows: Anthropogenic forcing follows emission paths corresponding to the A1B and A2 scenarios from the IPCC SRES (Bern-CC model (reference) output from Appendix II of *Intergovernmental Panel on Climate Change* [2001]), and volcanic forcing is constructed by randomly distributing the forcings of 20th-century eruptions over the 21st to avoid artificial drift of the model resulting from an unnatural lack of volcanic forcing. Three simulation experiments with different solar forcing have been performed: One with the last 11-year solar activity cycle repeated until 2100, and two with the Sun entering a new grand minimum. These grand minimum experiments follow the same logic as the different solar forcings for the millennium simulations described above, i.e., one has a total solar irradiance 0.08% below its value in 1950, while the reduction in solar irradiance is 0.25% relative to 1950 for the other [*Jansen et al.*, 2007]. In both scenarios the TSI is set to decrease with a rate similar to the one observed for an 11-year cycle, with the grand minimum beginning in 2010 for the higher TSI value and in 2025 for the lower TSI value, respectively, and continuing until the end of the century.

2.4. Model Response to Solar Activity Variations

[11] Variations of solar activity do not only change the total solar irradiance, but also its frequency distribution. The amplitude of the associated irradiance variations in the ultraviolet, for example, is much larger than in the optical, and it has long been suspected that these could have a discernible climate influence via, at present, inadequately understood feedback mechanism [e.g., *Lean*, 1997]. This kind of feedback is not represented in our climate model and could, in principle, lead to an underestimate of the climate response associated with solar variability. Indeed, the temperature changes corresponding to the 11-year solar activity cycle have an amplitude of ~0.025°C in our model, about a factor of 2 smaller than current estimates from the climate record [*Lean and Rind*, 2008]. It should be pointed out, however, that – depending on the feedback mechanism – the climate response to this short-term variability need not be the same as for the more prolonged grand minima.

[12] To assess how the model used in this study responds to pronounced long-lasting minima in solar forcing, we take the modelled values for the global mean temperature averaged over the time intervals of past grand minima of solar activity and compare them to a reconstruction of past global temperatures [*Mann et al.*, 2008] (see Table 1 and Figure 1). For the Wolf, Spörer, Maunder, and Dalton minima, the model driven with weak variations of solar forcing (MM TSI 0.08% below 1950) shows excellent agreement with

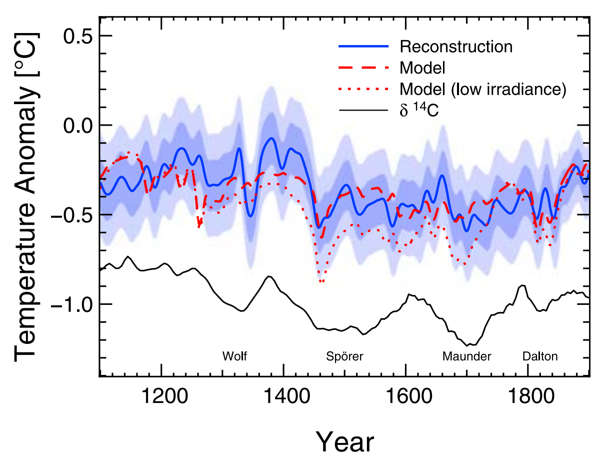

Figure 1. Comparison of global temperature reconstructions (using the "EIV HadCRUT3v land+ocean" data-set [*Mann et al.*, 2008]) (blue line with shaded errors) and the model simulations with solar forcing corresponding to recent reconstructions of total solar irradiance (TSI, red dashed line) and lower TSI (red dotted line) for the time interval 1100–1900. Both data and model output have been smoothed by applying singular spectrum analysis [*Moore et al.*, 2005] using an embedding dimension of 11 years. The black line indicates solar activity as traced by carbon-14 deviations (arbitrary units [*Reimer et al.*, 2004]), with the four grand minima during this time period (Wolf, Spörer, Maunder, and Dalton) labelled. The forcings used in the model are shown in Figure 6.14 of *Jansen et al.* [2007].

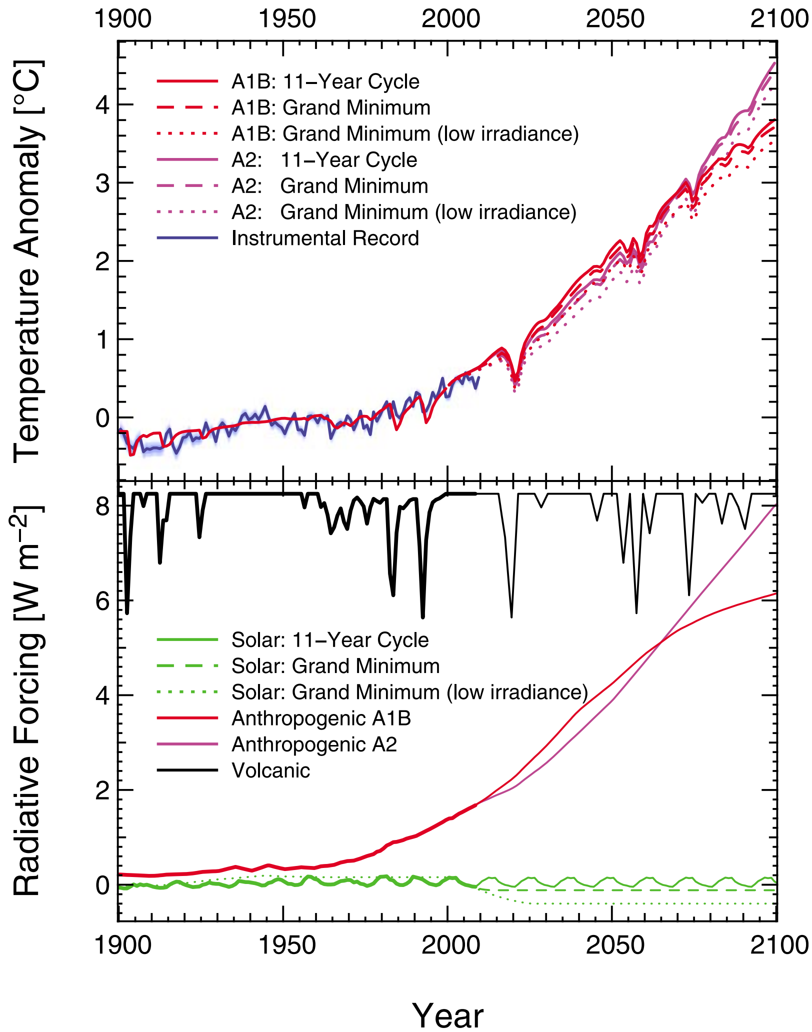

Figure 2. (top) Global mean temperature anomalies 1900–2100 relative to the period 1961–1990 for the A1B (red lines) and A2 (magenta lines) scenarios and for three different solar forcings corresponding to a typical 11-year cycle (solid line) and to a new grand minimum with solar irradiance corresponding to recent reconstructions of Maunder-minimum irradiance (dashed line) and a lower irradiance (dotted line), respectively. Observed temperatures until 2009 are also shown (NASA GISS [*Hansen et al.*, 2006], blue line and shaded 1σ and 2σ error ranges). (bottom) Radiative forcings used in the simulation experiments, with observed values until 2008 marked by thick lines. Volcanic radiative forcing has been shifted by +8.25 W m^{-2} for clarity.

reconstructed temperature anomalies relative to 1961–1990, while for a stronger decrease of solar activity during grand minima (MM TSI 0.25% below 1950) modelled temperatures are about 0.15°C cooler. At first sight this appears to favor the low-amplitude TSI history, but cannot exclude the high-amplitude variations of solar irradiance due to uncertainties in the reconstructed forcings and temperatures as well as in climate sensitivity. Indeed, the high-amplitude forcing is still within the 2 σ uncertainty range of the global temperature reconstructions shown in Figure 1.

[13] Uncertainties in the reconstruction of volcanic forcings and their influence on global temperatures over the last millennium [*Hegerl et al.*, 2006] add a further complication, because past grand minima of solar activity tend to coincide with series of large volcanic eruptions [*Bauer et al.*, 2003]. While the cooling during some volcanic episodes appears to be slightly overestimated in our model (possibly suggesting an underestimate of the effect of solar activity), it has recently been argued that current reconstructions of volcanic forcing underestimate the magnitude of eruptions [*Crowley et al.*, 2008] (suggesting the opposite). Further research is needed to resolve this issue.

3. Results and Conclusions

[14] Results for the evolution of the global mean temperature until the year 2100 show only a small temperature decrease of a future grand minimum of solar activity compared to standard scenarios. The global temperatures for the three different solar-forcing scenarios are shown in Figure 2 (top). With a continued 11-year solar activity cycle similar to the last cycle and volcanic eruptions similar to the 20th century, global temperatures are modelled to rise 3.7°C and 4.5°C above the 1961–1990 average level until the year 2100 for the A1B and A2 scenarios, respectively, in good agreement with recent projections [*Meehl et al.*, 2007]. The

average temperature rise in the time interval 2000–2030 is 0.23 ± 0.03° and 0.20 ± 0.03° per decade for the A1B and A2 scenarios, respectively. *Lean and Rind* [2009] used an empirical model to project a future average warming of 0.17 ± 0.03° per decade until 2030. This value is in good agreement with the predicted warming from our simulations, but somewhat smaller due to the slower rise of their assumed anthropogenic forcing.

[15] For a new grand minimum of solar activity with solar forcing corresponding to the currently favored reconstruction of MM solar irradiance (TSI 0.08% below 1950), the temperature in 2100 in the A1B scenario lies only 0.09°C lower, while for the experiment with a stronger variation in solar forcing (TSI 0.25% below 1950) the difference is 0.26°C. The corresponding values for the A2 scenario are very similar (0.10°C and 0.26°C). Recently, *Song et al.* [2010] performed idealised modelling experiments using the asymptotic IPCC B1 greenhouse gas concentrations, two fixed values for the TSI and no volcanic forcing and found a temperature offset of about 0.25°C for a TSI reduction of 0.2%, which is comparable to our strong solar forcing experiment.

[16] A map of the annual mean temperature differences between a new grand minimum and a continued 11-year solar activity cycle is shown in Figure 3. Cooling is strongest in polar and continental regions as well as over the Tibetan plateau, similar to recent reconstructions of the historic MM [*Mann et al.*, 2009]. A comparison of annual mean temperatures between a new grand minimum under the A1B scenario and the MM (see Figure 4) reveals exceptionally strong warming in polar regions, pointing to the importance of the ice-albedo feedback mechanism. Indeed, compared to 1971–2000 the annual mean sea-ice cover is modelled to be larger by ~10% during the MM (1681–1710) and ~40% smaller by the end of the century (2071–2100) for all scenarios. Moreover, for both future emission scenarios, the annual mean sea-ice area is larger by 2% and 4% for the different grand minimum forcings as compared to a continuing 11-year solar cycle.

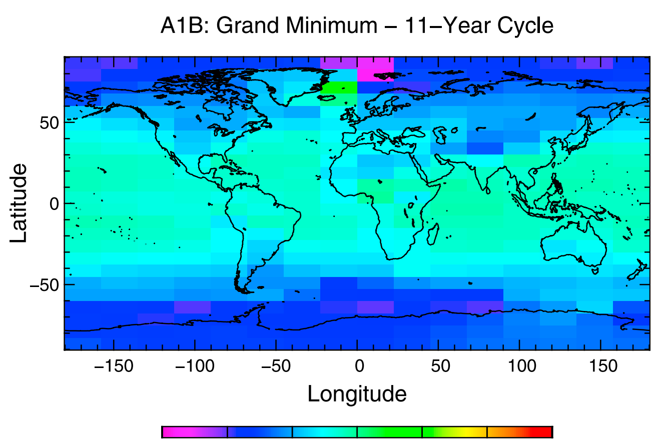

Figure 3. Map of the difference of annual mean surface temperatures between a new grand minimum (TSI 0.08% below 1950) in the 21st century and a continued cyclic solar activity for the IPCC A1B scenario. Temperatures were averaged over the period 2071–2100.

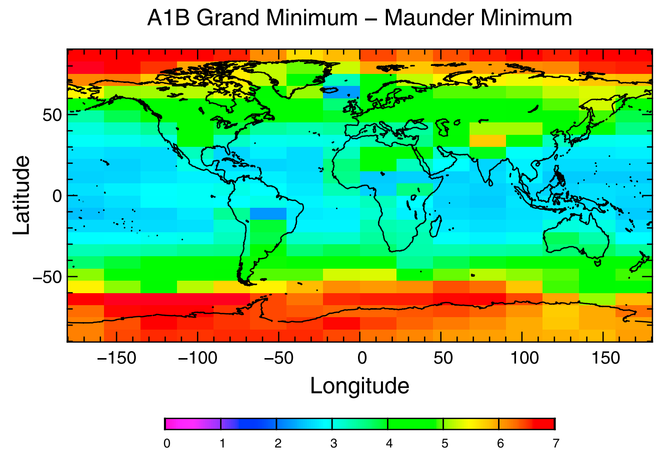

Figure 4. Temperature differences between a future grand minimum under the A1B scenario and the historic Maunder Minimum. Averages were performed over the periods 2071–2100 and 1681–1710, respectively.

[17] In summary, global mean temperatures in the year 2100 would most likely be diminished by about 0.1°C. Even taking into account all uncertainties in the temperature reconstruction, the forcings, and the model physics, the overall uncertainty is estimated to be at most a factor of 3, so the offset should not be larger than 0.3°C. Comparing this to the 3.7°C and 4.5°C temperature rise relative to 1961–1990 until the end of the century under the IPCC A1B and A2 emission scenarios, respectively, a new Maunder-type solar activity minimum cannot offset the global warming caused by human greenhouse gas emissions. Moreover, any offset of global warming due to a grand minimum of solar activity would be merely a temporary effect, since the distinct solar minima during the last millennium typically lasted for only several decades or a century at most.

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