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Are the most recent estimates for Maunder Minimum solar irradiance in agreement with temperature reconstructions?

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[1] Estimates for the total solar irradiance (TSI) during the 17th-century Maunder Minimum published in the last few years have pointed towards a TSI difference of 0.2–0.7 W m^{-2} as compared to the 2008/2009 solar minimum. Two recent studies, however, give anomalies which differ from this emerging consensus. The first study indicates an even smaller TSI difference, placing the Maunder Minimum TSI on the same level as the 2008/2009 minimum. The second study on the other hand suggests a very large TSI difference of 5.8 W m^{-2}. Here I use coupled climate simulations to assess the implications of these two estimates on Northern-hemisphere surface air temperatures over the past millennium. Using a solar forcing corresponding to the estimate of the first study, simulated Northern-hemisphere temperatures over the past millennium are consistent with reconstructed surface air temperatures. The large TSI differences between times of high and low solar activity as suggested by the second study, however, yield temperatures during all past grand solar minima that are too low, an excessive variance in Northern-hemisphere temperature on timescales of 50–100 years as compared to reconstructions, and temperatures during the first half of the 20th century which are too low and inconsistent with the instrumental temperature record. In summary this suggests a more moderate TSI difference of less than 1 W m^{-2} and possibly as low as 0–0.3 W m^{-2}.
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1. Introduction

[2] Reconstructing the past evolution of total solar irradiance (TSI) remains a challenge because we have to rely on indirect methods based on of proxies like sunspot number, geomagnetic activity or cosmogenic isotopes and different modeling approaches [*Fröhlich and Lean*, 2004]. Of particular importance are TSI estimates for the late-17th-century, when sunspot activity was exceptionally low. This "Maunder Minimum" has been associated with cooler climatic conditions during the "Little Ice Age" [*Eddy*, 1976] and thus offers the possibility to test the influence of solar activity on Earth's climate on multi-decadal time-scales.

[3] Early estimates for the solar irradiance during the Maunder Minimum mostly correspond to a relatively large TSI difference in the range 2–4 W m^{-2} between today and the end of the 17th century. (All TSI differences in this paper are expressed relative to the 2008/2009 solar minimum.) In the past few years, however, a number of studies consistently placed this difference at markedly lower values of 0.2–0.7 W m^{-2}, converging towards the lower end of the this range (see the review by *Gray et al.* [2010]).

[4] Two recent estimates of Maunder Minimum TSI challenge this emerging consensus, however [*Lockwood*, 2011]. *Schrijver et al.* [2011] argue that solar conditions during the recent 2008/2009 minimum may be a good indicator for minimal solar activity and hence TSI during the Maunder Minimum. *Shapiro et al.* [2011], on the other hand, present a TSI reconstruction based on assumed changes of the quiet-Sun irradiance which can be modeled with the long-term changes of the production rate of the ^{10}Be record, scaled in order to agree within the range of the three available TSI composites. They find a Maunder Minimum TSI 5.8 W m^{-2} below the 2008/2009 solar minimum, an anomaly which is considerably larger than any previous estimate (see Figure 1a).

[5] In this paper, the implications of these two TSI estimates on Northern-hemisphere surface air temperatures are explored using coupled climate simulations over the past millennium. In particular, the simulated temperatures are compared to a temperature reconstruction over this period of time, testing for the first time whether these TSI estimates are consistent with the climate record. In principle, this offers the possibility to constrain TSI variations independent of solar-activity proxies and models.

2. Climate Model Experiments

2.1. Model Description

[6] The simulations in this paper were performed with the coupled intermediate-complexity climate model CLIMBER-3α [*Montoya et al.*, 2006]. The model's main components are an ocean general-circulation model [*Pacanowski and Griffies*, 1999] with a horizontal resolution of 3.75° by 3.75° and 24 vertical levels, and a statistical-dynamical atmosphere [*Petoukhov et al.*, 2000] with a relatively coarse resolution of 22.5° in longitude and 7.5° in latitude with 16 vertical layers. CLIMBER-3α's equilibrium climate sensitivity is 3.4°C.

2.2. Simulation Experiments

[7] All model experiments were started from an equilibrium simulation with a constant CO_2 concentration of 277 ppm and a solar constant of 1361 W m^{-2}, close to the recent estimate from SORCE/TIM [*Kopp and Lean*, 2011]. This simulation was integrated for 2000 years and continued as control experiment to correct the actual model experiments for a small residual drift in Northern-hemisphere temperature (below 10^{-5} °C/yr).

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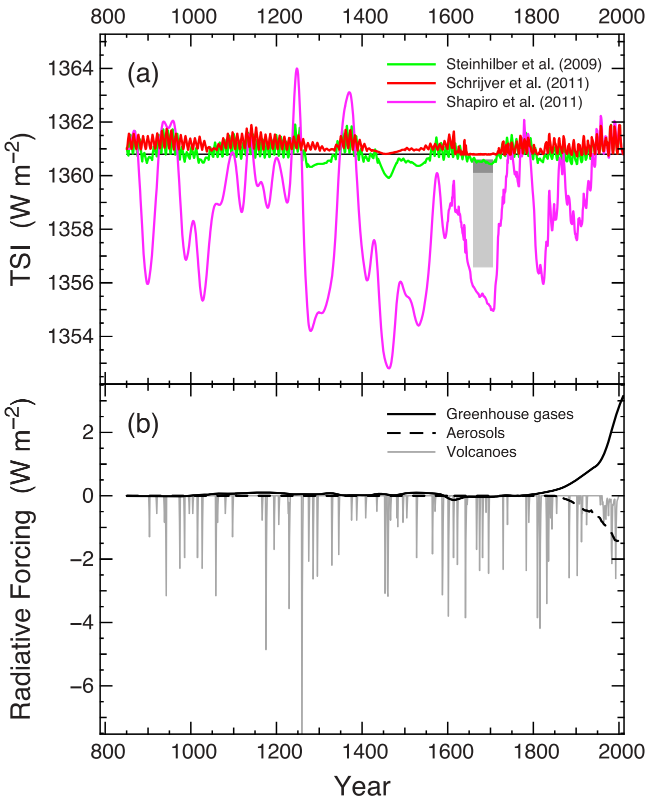

Figure 1. (a) TSI reconstructions based on *Steinhilber et al.* [2009] (green), *Schrijver et al.* [2011] (red) and *Shapiro et al.* [2011] (magenta) used in the climate model experiments. All have been scaled to the TSI measured during the recent 2008/2009 solar minimum [*Kopp and Lean*, 2011] indicated by the black line. The full range of previous estimates for the Maunder Minimum TSI is shown as lightly shaded area, whereas the darker shading denotes the more moderate values for the TSI difference derived in recent years, in this study represented by *Steinhilber et al.*'s [2009] reconstruction. (b) Radiative forcings used in the simulations: greenhouse gases and tropospheric ozone (solid black line), anthropogenic aerosols (dashed black line) and volcanic aerosols (grey). Note that the period 850–1000 is used only for model spin-up.

[8] Greenhouse gas and anthropogenic aerosol forcings for the millennium simulations follow the Paleoclimate Modelling Intercomparison Project Phase 3 (PMIP3) recommendations [*Schmidt et al.*, 2011] and *Joos et al.* [2001] for the pre-industrial and industrial period, respectively, while the volcanic aerosol forcing is taken from *Crowley* [2000]. All forcings are shown in Figure 1b. Long-term changes of Earth's orbital parameters were taken into account following *Berger* [1978].

[9] Model experiments with three different TSI scenarios were performed. *Schrijver et al.* [2011] provide an estimate for the Maunder Minimum TSI rather than a full reconstruction. Therefore, the TSI for this model experiment was constructed by taking the reconstruction by *Wang et al.* [2005] without the background component for the years after 1610 and extending it back to the year 850 following *Delaygue and Bard* [2011] with a synthetic 11-year solar activity cycle. TSI values for the last years were added using data from SORCE/TIM and normalised to a value of 1360.8 W m^{-2} during the 2008/2009 minimum [*Kopp and Lean*, 2011]. *Shapiro et al.*'s [2011] TSI reconstruction for the second millennium simulation was provided by the authors and was normalised in the same way. In addition, one simulation with *Steinhilber et al.*'s [2009] TSI reconstruction was performed, supplemented by *Wang et al.*'s [2005] TSI (including the background component) for the time since 1850 (following the PMIP3 recommendations). All three TSI scenarios are shown in Figure 1a.

[10] The simulation experiments used a spin-up period of 150 years before the actual millennium simulations and were integrated until the year 2010. The spin-up time was chosen because around 850 all three TSI reconstructions are very similar to each other and very close to the value of 1361 W/m^2 used in the equilibrium run. The volcanic forcing for the spin-up period from 850–1000 was mirrored from the years 1000–1150 to avoid a cold start of the model.

3. Results

[11] A comparison of the modeled Northern-hemisphere temperature evolution over the past millennium with the ensemble temperature reconstruction computed by *Frank et al.* [2010] is shown in Figure 2. Global temperatures simulated with a TSI evolution based on *Steinhilber et al.*

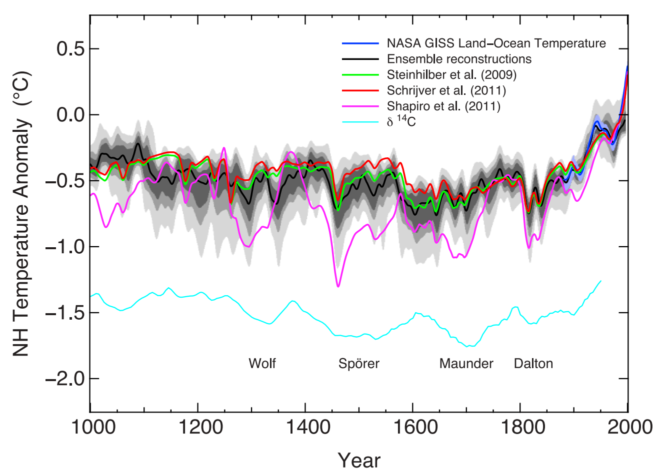

Figure 2. Northern-hemisphere surface air temperatures anomalies (relative to 1971–2000) for the past millennium. Instrumental land-ocean temperatures are shown in blue (NASA-GISS [*Hansen et al.*, 2010]), with 2σ uncertainties indicated by the light blue shading. The 50% quantile of the ensemble temperature reconstruction by *Frank et al.* [2010] is shown in black. The shaded regions (from light to dark grey) indicate the ranges covered by 90%, 70% and 50% of the ensemble reconstructions. The results of the model simulations with the *Steinhilber et al.* [2009], *Schrijver et al.* [2011] and *Shapiro et al.* [2011] solar forcings are presented in green, red and magenta, respectively. All temperature curves have been smoothed using singular spectrum analysis [*Ghil et al.*, 2002], the simulated temperatures with embedding M = 11, the reconstructed temperatures with M = 8 since they are already smoothed over 10-year periods. The ^{14}C record (arbitrary units [*Reimer et al.*, 2004]) is shown in cyan, with labels indicating past grand solar minima.

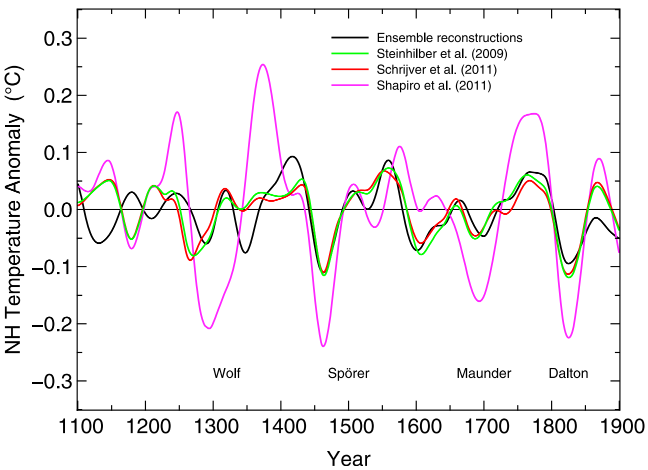

Figure 3. Fluctuations of Northern-hemisphere surface air temperatures on timescales of about half a century from the ensemble temperature reconstructions (black [*Frank et al.*, 2010]) and from the model simulations with *Steinhilber et al.*'s [2009] (green), *Schrijver et al.*'s [2011] (red) and *Shapiro et al.*'s [2011] (magenta) solar forcings. Prominent grand solar minima during the last millennium are marked in the lower part of the panel.

[2009] and *Schrijver et al.* [2011] lie well within the range covered by most of the temperature reconstructions in the ensemble, with *Steinhilber et al.*'s [2009] simulation showing marginally better agreement in the time period between 1300 and 1700 [see also *Foukal et al.*, 2006]. This is not the case for *Shapiro et al.*'s [2011] TSI reconstruction which consistently yields temperatures during the past grand minima of solar activity that are too low.

[12] Of particular concern are the underestimated surface air temperatures for the first half of the 20th century, where *Shapiro et al.*'s [2011] reconstruction shows a steep rise of the TSI (see Figure 1a). During this time interval, temperatures are derived from the instrumental record and are thus much better constrained than for earlier times, so the discrepancy suggests that *Shapiro et al.*'s [2011] TSI exhibits too strong variations with solar activity. *Shapiro et al.* [2011] cautiously note the agreement of their reconstruction with the Smithsonian Astrophysical Observatory (SAO) TSI measurements from the first half of the 20th century [*Aldrich and Hoover*, 1954]. It should be emphasised, however, that this agreement cannot provide confirmation for a strong rise in TSI during this period of time due to systematic effects in the SAO data, see for example the discussions by *Allen* [1958], *Ångström* [1970] and *Feulner* [2011].

[13] Note that the model used here is forced only by the variation in TSI, not the effects of changes in the solar spectral irradiance, in particular the variations in the ultraviolet part of the electromagnetic spectrum [see, e.g., *Haigh et al.*, 2010]. Including these effects would presumably enlarge the temperature difference between times of high and low solar activity, and thus could further enhance the discrepancy between the reconstruction and the temperatures based on *Shapiro et al.* [2011].

[14] Another, and arguably more robust, way to analyse differences between the simulated and reconstructed temperatures is to look at the amplitude of temperature fluctuations on timescales of about half a century. To compute these, the long-term trend in the temperatures is subtracted using singular spectrum analysis [*Ghil et al.*, 2002] with embedding $M = 100$, before the residuals are again smoothed with embedding $M = 30$ to remove fluctuations on shorter timescales. The result of this exercise is shown in Figure 3: While the variance of modeled Northern-hemispheric temperature fluctuations of 0.05°C and 0.04° for *Steinhilber et al.*'s [2009] and *Schrijver et al.*'s [2011] TSI agree remarkably well with the amplitude of the ensemble reconstruction (0.05°C), *Shapiro et al.*'s [2011] TSI yields excessive amplitudes of 0.1°C. This result is robust with respect to changes of the smoothing parameters. Furthermore, simulations with the volcanic forcing decreased by 35% (the typical uncertainty in volcanic forcing [*Hegerl et al.*, 2006]) for *Shapiro et al.*'s [2011] simulation and increased by 35% for *Schrijver et al.*'s [2011] experiment change the values of the variances by only 0.01°C.

4. Implications for Future Grand Minimum

[15] Here I briefly revisit the question how much a 21st-century grand solar minimum [*Lockwood*, 2010] would influence the future climate [*Wigley and Kelly*, 1990; *Thomas and Weiss*, 2008; *Feulner and Rahmstorf*, 2010; *Song et al.*, 2010]. To this end, the simulations were continued until the year 2100 with anthropogenic forcing following the new Representative Concentration Pathways (RCPs) [*Moss et al.*, 2010] RCP3PD, RCP4.5, RCP6 and RCP8.5, without volcanic forcing, and with three solar forcings scenarios corresponding to a repeated cycle 23 (with minima on the 2008/2009 TSI level) as well as transitions to a new grand solar minimum beginning after cycle 24 and lasting until 2100 with TSI levels of 1361 W m^{-2} and 1355 W m^{-2} as in Figure 1b.

[16] For all RCPs, a 21st-century grand solar minimum with a TSI as estimated by *Schrijver et al.* [2011] leads to global temperatures during 2071–2100 which are by 0.04°C lower as compared to a continuing 11-year solar activity cycle. Note that our model underestimates the temperature response to the 11-year solar cycle [*Lean and Rind*, 2008], thus a temperature offset of 0.1°C is a more realistic value. The temperature offset due to a minimum with a TSI value corresponding to *Shapiro et al.*'s [2011] reconstruction is considerably larger (0.5°C), but rather unrealistic as shown for the reconstruction back to the Maunder Minimum. In any case, these values are smaller than the increase of global surface temperatures of 1.4–4.8°C relative to preindustrial times expected from the RCPs by 2100.

5. Discussion and Conclusions

[17] I have analysed the climatic implications of two recent reconstructions of the TSI during the Maunder Minimum, one suggesting a late-17th-century TSI on the same level as the most recent solar minimum [*Schrijver et al.*, 2011], the other indicating a very large difference of 5.8 W m^{-2} [*Shapiro et al.*, 2011]. A comparison of reconstructions of Northern-hemisphere surface air temperatures over the past millennium with simulated temperatures for these TSI scenarios yields climatic conditions during past solar minima that are too cool and excessive fluctuations on timescales of several decades for *Shapiro et al.*'s [2011] TSI reconstruction. These results favour a more moderate

difference in TSI between today and the Maunder Minimum, in agreement with several other recent TSI reconstructions. Determining an upper limit for the TSI difference during the Maunder Minimum remains difficult due to the uncertainties in climate forcings, sensitivity and temperature reconstructions, but the TSI difference is most likely not larger than 1 W m^{-2}, and possibly much smaller. Indeed, the excellent agreement of the temperature fluctuations based on small Maunder Minimum TSI differences shows that the value could be as small as 0–0.3 W m^{-2}. This also illustrates that TSI variations may not be the dominant driver of lower temperatures during the Little Ice Age, but note that regional and seasonal responses should be explored in more detail.

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