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Total solar irradiance during the Holocene

F. Steinhilber,[1] J. Beer,[1] and C. Fröhlich[2]

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[1] For the first time a record of total solar irradiance covering 9300 years is presented, which covers almost the entire Holocene. This reconstruction is based on a recently observationally derived relationship between total solar irradiance and the open solar magnetic field. Here we show that the open solar magnetic field can be obtained from the cosmogenic radionuclide ^{10}Be measured in ice cores. Thus, ^{10}Be allows to reconstruct total solar irradiance much further back than the existing record of the sunspot number which is usually used to reconstruct total solar irradiance. The resulting increase in solar-cycle averaged TSI from the Maunder Minimum to the present amounts to (0.9 ± 0.4) Wm^{-2}. In combination with climate models, our reconstruction offers the possibility to test the claimed links between climate and TSI forcing. **Citation:** Steinhilber, F., J. Beer, and C. Fröhlich (2009), Total solar irradiance during the Holocene, *Geophys. Res. Lett.*, *36*, L19704, doi:10.1029/2009GL040142.

1. Introduction

[2] The Sun is the main driver of the Earth's climate. There is growing evidence [e.g., *Neff et al.*, 2001; *Bond et al.*, 2001; *Wanner et al.*, 2008] that many past climate changes coincide with changes in solar activity which may also change total solar irradiance (TSI). This raises questions about the Sun's role in the climate in the past, present, and therefore even in the future. To answer these questions, the quantitative solar forcing has to be known not only for the present period of high solar activity, but also for periods when the Sun was very quiet, such as the Maunder Minimum (MM).

[3] That solar activity during the MM was substantially reduced is manifested by the lack of sunspots (see also Figure 1a). Although sunspots are dark, the Sun is brighter during solar maxima which is related to the bright faculae in active regions and the network, so it could well be that the Sun was fainter during periods of low activity. Models taking these surface manifestations of solar activity into account do reproduce the observed TSI variation extremely well on daily to 11-year solar cycle time scales [*Foukal et al.*, 2006; *Krivova and Solanki*, 2008]. Besides this periodic solar-cycle variation, the amplitude of the sunspot number shows a secular change varying from essentially zero during the MM to over 180 in 1959 (dashed line in Figure 1a). This raises the question about how TSI is related to such long-term changes in the activity level and what could have been the level during the MM. The answer is not only relevant for our understanding of the Sun, but is of special interest for climate studies.

[4] Up to now, reconstructions of TSI were based on the assumption that both the solar-cycle modulation and the long-term changes are due to manifestations of surface magnetism [e.g., *Wang et al.*, 2005; *Krivova et al.*, 2007]. In this study we use another approach by considering the knowledge about TSI obtained during the observational period (1978 to the present). Hereby, TSI is represented by the PMOD composite, mainly because it provides a reliable record also during the solar cycle 21 (for details see *Fröhlich* [2009]).

[5] During the solar minimum in 2008/09 the PMOD composite shows that TSI is much lower than it was during the previous minimum in 1996 and the fact, that, e.g., the chromospheric indices and thus the UV radiation do not show a similar distinct decrease, indicates that the long-term trend of TSI is not due to changes of the surface magnetism but a different mechanism. This must, however, be still related to the overall level of activity and it may be due to a change in global temperature of the Sun as already suggested by *Tapping et al.* [2007]. Moreover, *Fröhlich* [2009] shows that there is a strong correlation between TSI and the open magnetic field B_r during the time of the minima of the observed 30-year-long TSI record. This correlation can be used for reconstructing TSI during minima times whenever B_r is known.

2. Reconstruction of Solar Magnetic Field

[6] To determine the strength of the open solar magnetic field B_r in the past, we make use of the fact that it modulates the intensity of the galactic cosmic rays traveling through the heliosphere.

[7] The galactic cosmic rays enter the Earth's atmosphere where they interact with nitrogen and oxygen atoms producing ^{10}Be. Thus, the ^{10}Be signal is a proxy of the open solar magnetic field.

[8] After production ^{10}Be becomes attached to aerosols and is removed from the atmosphere within approximately one year. The atmospheric transport of ^{10}Be introduces some climatic noise but general circulation model simulations show that the amplitude of this noise is relatively small compared to the production signal [*Heikkilä et al.*, 2008]. Besides solar activity also the geomagnetic field modulates the cosmic ray intensity. Thus, by considering the temporal variation of the geomagnetic field intensity, ^{10}Be measurements in ice cores offer the possibility to reconstruct the modulation of the cosmic ray intensity in the heliosphere. The cosmic ray intensity can be parameterized by the so-called solar modulation potential, ϕ.

[1]Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland.
[2]Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, Davos Dorf, Switzerland.

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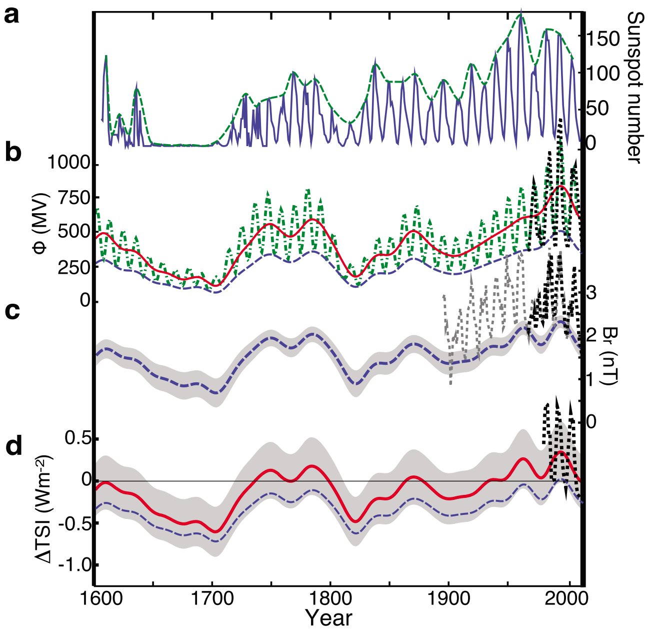

Figure 1. Data since 1600 including the solar minimum 2008. (a) Group sunspot number. The full line are annual values, and the dashed line is the envelope going through the 11-year solar cycle maxima. (b) Solar modulation potential ϕ. The full line shows 40-year averages of ϕ. The dash-dotted line is ϕ extended with estimated 11-year solar cycle variations. The dashed line is the lower envelope. Black dotted are annual averages of ϕ from neutron monitor count rates (calculated by the US Federal Aviation Administration). (c) Open solar magnetic field B_r. The dashed line is B_r during the 11-year solar cycle minima derived from ϕ using equation (3). The shaded band is the 1σ uncertainty derived from equation (3) considering the uncertainties in ϕ and the exponent α. Dotted are annual averages of B_r (back to 1963) from the OMNI dataset and of the reconstruction of *Rouillard et al.* [2007] (back to 1895). (d) TSI relative to the value of the PMOD composite during the solar cycle minimum of the year 1986 (1365.57 Wm^{-2}). The dashed line is TSI during the 11-year solar cycle minima and the full line is solar cycle averaged TSI. Black dotted are annual averages of the PMOD composite.

[9] Recently, a ϕ composite [*Steinhilber et al.*, 2008] has been built from individual ϕ records [*Vonmoos et al.*, 2006; *McCracken et al.*, 2004; *Usoskin et al.*, 2005] which are based on the cosmogenic radionuclide ^{10}Be measured in ice cores and on neutron monitor count rates. The composite is a 40-year running-mean covering the past 9300 years.

[10] As shown by the full line in Figure 1b the ϕ composite resembles the sunspot number amplitude which illustrates that ϕ is related with solar magnetic activity, i.e., the strength of the open solar magnetic field [*Caballero-Lopez et al.*, 2004; *McCracken*, 2007].

[11] During the past few decades the Sun has been very active with solar cycle minima values of ϕ of about 400 MV whereas during periods of low solar activity, such as the MM, ϕ was only about 180 MV. We stress that the difference in ϕ between MM and the present is larger than its uncertainty of 80 MV [*Steinhilber et al.*, 2008] and therewith ϕ can be used for quantitative studies of the open solar magnetic field.

[12] In order to define the 11-year solar cycle minima values of ϕ, for which *Fröhlich* [2009] has found the TSI-B_r relationship, a sinusoidal variation with a period of 11 years has been added to the 40-year averages of the ϕ composite (dash-dotted line in Figure 1b). Thereby, the amplitude of the individual solar cycles were scaled to the 40-year means of ϕ in agreement with 11-year cycle variations in annual ^{10}Be data during the MM [*McCracken and Beer*, 2007] and in neutron monitor count rates of the present (dotted line in Figure 1b). We note that this 11-year cycle has not a physical meaning like the observed sunspot cycle but serves as a good approximation of the cycle minima values. These are represented by the lower envelope (dashed line in Figure 1b).

[13] The relationship between the cosmic ray intensity and the open solar magnetic field B_{IMF} is given by a power law [*Caballero-Lopez et al.*, 2004; *McCracken*, 2007]. Recently, *Steinhilber et al.* [2009] derived the analytical relationship between B_{IMF} and ϕ

$$B_{\mathrm{IMF}}(t) = B_{\mathrm{IMF},0} \times \left(\frac{\phi(t)}{\phi_0}\frac{v_{\mathrm{SW},0}}{v_{\mathrm{SW}}}\right)^{1/\alpha}, \quad (1)$$

where v_{SW} is the solar wind speed and $B_{\mathrm{IMF},0}$, ϕ_0, and $v_{\mathrm{SW},0}$ are normalization factors. The normalization factors are the mean values of the 11-year solar cycle minima in the observation period (1965–2008): ϕ_0 = 380 MV, $B_{\mathrm{IMF},0}$ = 5.3 nT, $v_{\mathrm{SW},0}$ = 414 km s^{-1}. We found the exponent of the power law in equation (1) to be $\alpha = 1.7 \pm 0.3$ similar to *Rouillard and Lockwood* [2007]; *McCracken* [2007]; and Steinhilber et al. (submitted manuscript, 2009). Figure 3 illustrates that our method is able to reconstruct the observed B_{IMF} during the 11-year solar cycle minima from the OMNI dataset. We note that our reconstruction is even able to get the very low values of B_{IMF} during the last solar minimum around the year 2008.

[14] To apply the TSI-B_r relationship of *Fröhlich* [2009] the radial component B_r of the interplanetary magnetic field is needed. This is related with B_{IMF} via the Parker spiral [*Parker*, 1958]

$$|B_r(t)| = B_{\mathrm{IMF}}(t) \times \left[1 + \left(\frac{R_{\mathrm{SE}}\,\omega\cos\Psi}{v_{\mathrm{SW}}(t)}\right)^2\right]^{-1/2}, \quad (2)$$

where R_{SE} is the mean Sun-Earth distance, ω is the equatorial angular solar rotation rate, and Ψ is the heliographic latitude. Combining equations (1) and (2) gives the relationship between ϕ and B_r

$$|B_r(t)| = 0.56\, B_{\mathrm{IMF},0} \times \left(\frac{\phi(t)}{\phi_0}\frac{v_{\mathrm{SW},0}}{v_{\mathrm{SW}}(t)}\right)^{1/\alpha} \times \left[1 + \left(\frac{R_{\mathrm{SE}}\,\omega\cos\Psi}{v_{\mathrm{SW}}(t)}\right)^2\right]^{-1/2}. \quad (3)$$

[15] The additionally factor of 0.56 in equation (3) adjusts the radial field obtained from Parker spiral theory due to differences between measurements of the open

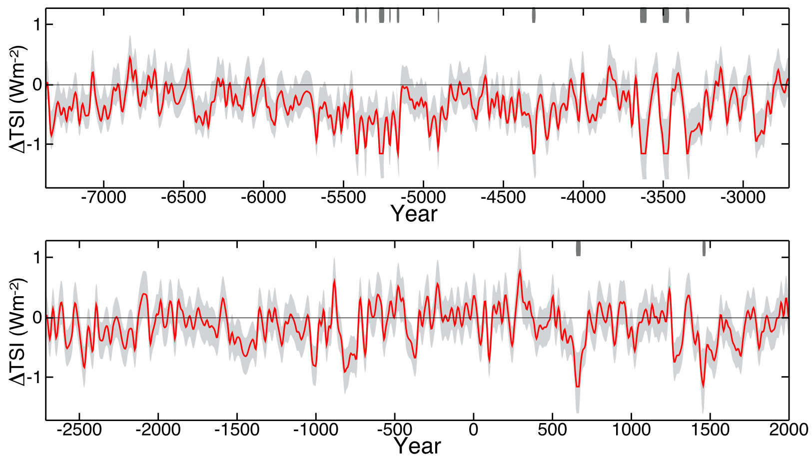

Figure 2. 40-year (cycle) averaged TSI for the past 9300 years based on its relationship with B_r relative to the value of the PMOD composite during the solar cycle minimum of the year 1986 (1365.57 Wm^{-2}). The shaded band is the 1σ uncertainty considering the uncertainties of the TSI-B_r calibration and of the reconstruction of B_r. The bars in the top of each plot mark periods when TSI reaches the minimum value of 1364.64 Wm^{-2} corresponding to ϕ = 0 MV and B_r = 0 nT. During these periods the uncertainty is not defined and was set to 0.5 Wm^{-2}.

solar magnetic field at 1 AU and at the solar source surface. The correction is found similar to *Rouillard et al.* [2007]. Equation (3) has two unknowns: 1) the product of R_{SE}, ω and cos Ψ, and 2) v_{SW}. R_{SE}, ω and cos Ψ are observed parameters and their product of annual averages is 397 km s^{-1}, which is a constant on the time scales considered in this study. So, the only remaining unknown is the solar wind speed.

[16] We estimated the influence of the solar wind speed on the reconstruction of B_r by changing its value during grand solar minima between half and twice its present value. It had no significant effect because the uncertainties in ϕ and α were larger. Thus an average present solar wind was used in the reconstructions of B_r.

[17] We applied equation (3) to reconstruct B_r and its uncertainty, considering the uncertainties in ϕ and the exponent α. The resulting curve is plotted in Figure 1c. It agrees well with the solar cycle minima values of observations (OMNI dataset) and the reconstruction of *Rouillard et al.* [2007] based on geomagnetic indices as displayed as dotted lines. Overall, the result of our approach is similar to those of other studies [e.g., *Lockwood et al.*, 1999; *Solanki et al.*, 2000; *Caballero-Lopez et al.*, 2004; *Wang et al.*, 2005; *McCracken*, 2007; *Rouillard et al.*, 2007; *Krivova et al.*, 2007]. However, differences occur during the MM. Reconstructions based on sunspots [*Solanki et al.*, 2000; *Krivova et al.*, 2007] show a vanished B_r, whereas our B_r is not zero in agreement with other reconstructions also based on cosmogenic radionuclides [*Caballero-Lopez et al.*, 2004; *McCracken*, 2007; Steinhilber et al., submitted manuscript, 2009].

3. Reconstruction of Total Solar Irradiance

[18] After converting ϕ into B_r, TSI is calculated using the TSI-B_r relationship of *Fröhlich* [2009]

$$\mathrm{TSI} = (1364.64 \pm 0.40)\,\mathrm{Wm}^{-2} + (0.38 \pm 0.17)\,\mathrm{Wm}^{-2}\,\mathrm{nT}^{-1}\,B_r. \qquad (4)$$

[19] The quoted uncertainties are quite conservative as given by *Fröhlich* [2009, Figure 4c] because all points lie on or very close to the regression line.

[20] The uncertainty of reconstructing TSI was estimated by accounting for the uncertainties of the reconstructed B_r and of the TSI-B_r relationship. From the latter we only considered the uncertainty of the slope since we were only interested in relative differences. The estimated 1σ uncertainty of our reconstruction is in the range of 0.3 to 0.5 Wm^{-2} with a mean value of 0.4 Wm^{-2}. The reconstructed TSI represents solar cycle minima values and is shown as the dashed line in Figure 1d. As can be seen our reconstruction agrees well with the PMOD composite [*Fröhlich*, 2009] during the 11-year solar cycle minima.

[21] However, it is the solar cycle averaged TSI which is relevant for long-term climate studies, which is added next.

[22] We made the rough estimate that the cycle amplitude in TSI scales linearly with the cycle average of the minima values of B_r. With a scaling of 0.42 Wm^{-2} nT^{-1} this assumption reproduces the amplitudes of the three observed

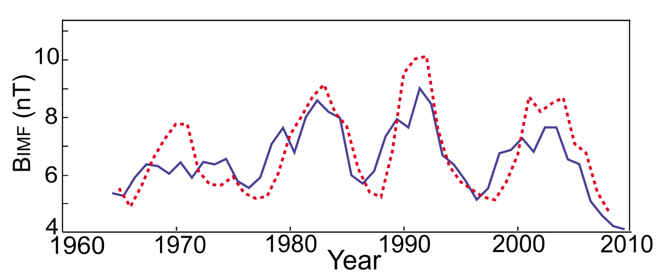

Figure 3. Comparison of observation and reconstruction of B_{IMF}. The full line are the observational data from the OMNI dataset. The dotted line is calculated with equation (1) using ϕ calculated from neutron monitor count rates (calculated by the US Federal Aviation Administration) assuming a constant solar wind speed.

Table 1. Increase of TSI in Wm^{-2} Between the MM and the Solar Cycle Average[a]

		Surface Magnetism			Solar-Type Stars	
Method Reference	This Study	W05	K07	T07	L95	L00
Year	1710	1700	1713	∼1670	1700	1700
-1σ	0.5		0.9	0.6		
mean	0.9	1	1.3	1	3.2	2.8
$+1\sigma$	1.3		1.5	1.4		

[a](1365.9 Wm^{-2}) of solar cycle 22 (1986–1996) of the PMOD composite [*Fröhlich*, 2009] in comparison with earlier reconstructions: W05 = *Wang et al.* [2005], K07 = *Krivova et al.* [2007], T07 = *Tapping et al.* [2007], L95 = *Lean et al.* [1995], L00 = *Lean* [2000].

cycles within ±11%, which is acceptable for the present reconstruction (for details about the cycle amplitudes see *Fröhlich* [2009]).

[23] The full line in Figure 1d shows the cycle averaged TSI since 1600. This epoch is characterized by the occurrence of three periods of low solar activity, the Maunder (1645–1715), Dalton (1790–1830) and Gleissberg (around 1900) minima, and the current period of high activity. TSI during the MM was slightly lower than during both the Dalton and the Gleissberg minima. The cycle averaged TSI during the MM was lower by (0.9 ± 0.4) Wm^{-2} compared to the observed mean value in the PMOD composite during solar cycle 22 (1986–1996). The corresponding differences between the minima and maxima levels during the MM and the solar cycle minimum in 1986 is (0.6 ± 0.4) and (0.9 ± 0.4) Wm^{-2}, respectively.

[24] The entire record of TSI covering the past 9300 years is shown in Figure 2. Throughout this period TSI has varied by approximately 2 Wm^{-2}. The average TSI of the entire period lies about 0.4 Wm^{-2} below the current values and is about 0.5 Wm^{-2} higher than the values during the MM.

[25] In most of the grand solar minima TSI has been similar than during the MM, illustrating that TSI of the MM is typical for grand solar minima.

[26] There exist some uncertainty on time-scales of millennia and longer. This is mainly due to uncertainties in the slowly changing geomagnetic field intensity, which is needed to calculate ϕ from ^{10}Be data. By re-calculating TSI with a second record of the geomagnetic field, we estimated this long-term uncertainty to be 0.3 Wm^{-2} which lies in the uncertainty range of the TSI reconstruction and thus do only marginally influence our results, i.e., grand solar minima do not turn into grand maxima and vice versa.

[27] It is important to note that equation (4) determines the lower limit of TSI. Assuming the extreme case, namely that the open magnetic field is zero, from this equation follows that the lowest possible value of TSI lies 0.93 Wm^{-2} below the PMOD composite in the year 1986.

4. Summary and Conclusion

[28] This is the first observationally and physics-based record of TSI for the past 9300 years. Starting from ^{10}Be measurements in polar ice we used the basic physical mechanisms to calculate the open solar magnetic field, from which TSI was derived. As ^{10}Be is the basis, the sunspot number record starting in 1610 is no longer a limitation on which all other TSI reconstructions are based. Moreover, it is interesting to note that our reconstruction shows a variation during the grand minima which indicates that the behaviour of solar activity during the grand minima is not just a lack of sunspots, but more complex.

[29] Our estimated difference between the MM and the present is (0.9 ± 0.4) Wm^{-2}. This is smaller by a factor of 2–4 compared to records [*Lean et al.*, 1995; *Lean*, 2000] that have been used in climate model studies. Although our result is similar to the values of other more recent reconstructions [e.g., *Wang et al.*, 2005; *Krivova et al.*, 2007; *Tapping et al.*, 2007] (see Table 1), the derivations are based on completely different assumptions, e.g., both *Wang et al.* [2005] and *Krivova et al.* [2007] use either the total photospheric magnetic field or the sum of the open field calculated from flux transport models using sunspot numbers and the fields from the ephemeral regions for the long-term change and determine TSI assuming that the change depends on the magnetic field in the same way as for the 11-year cycle modulation. In our approach the long-term changes of TSI do not dependent directly on B_r, but on the strength of the activity which is also well represented by B_r.

[30] This reconstruction provides a reliable basis for climate models to quantify the role of TSI forcing on the Earth climate over the past centuries and millennia as well as for estimating the possible solar influence in future. However, the limitations of only considering the rather small forcing by TSI changes may still be a problem. The UV irradiance may not be the viable solution because its observational data do not show a similar distinct decreasing trend as TSI [*Fröhlich*, 2009], implying that its level during the MM was similar as in present solar cycle minima. TSI data is numerically available as auxiliary material.[1]

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References

Bond, G., et al. (2001), Persistent solar influence on North Atlantic climate during the Holocene, *Science*, *294*, 2130–2136, doi:10.1126/science.1065680.

Caballero-Lopez, R. A., H. Moraal, K. G. McCracken, and F. B. McDonald (2004), The heliospheric magnetic field from 850 to 2000 AD inferred

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL040142.

from ^{10}Be records, *J. Geophys. Res.*, *109*, A12102, doi:10.1029/2004JA010633.

Foukal, P., C. Fröhlich, H. Spruit, and T. M. L. Wigley (2006), Variations in solar luminosity and their effect on the Earth's climate, *Nature*, *443*, 161–166, doi:10.1038/nature05072.

Fröhlich, C. (2009), Observational evidence of a long-term trend in total solar irradiance, *Astron. Astrophys.*, *501*, 27–30, doi:10.1051/0004-6361/200912318.

Heikkilä, U., J. Beer, and J. Feichter (2008), Modeling cosmogenic radionuclides ^{10}Be and ^{7}Be during the Maunder Minimum using the ECHAM5-HAM general circulation model, *Atmos. Chem. Phys.*, *8*, 2797–2809.

Krivova, N. A., and S. K. Solanki (2008), Models of solar irradiance variations: Current status, *Astron. Astrophys.*, *29*, 151–158, doi:10.1007/s12036-008-0018-x.

Krivova, N. A., L. Balmaceda, and S. K. Solanki (2007), Reconstruction of solar total irradiance since 1700 from the surface magnetic flux, *Astron. Astrophys.*, *467*, 335–346, doi:10.1051/0004-6361:20066725.

Lean, J. (2000), Evolution of the Sun's spectral irradiance since the Maunder Minimum, *Geophys. Res. Lett.*, *27*(16), 2425–2428, doi:10.1029/2000GL000043.

Lean, J., J. Beer, and R. Bradley (1995), Reconstruction of solar irradiance since 1610: Implications for climate change, *Geophys. Res. Lett.*, *22*(23), 3195–3198, doi:10.1029/95GL03093.

Lockwood, M., R. Stamper, and M. N. Wild (1999), A doubling of the Sun's coronal magnetic field during the past 100 years, *Nature*, *399*, 437–439, doi:10.1038/20867.

McCracken, K. G. (2007), Heliomagnetic field near Earth, 1428–2005, *J. Geophys. Res.*, *112*, A09106, doi:10.1029/2006JA012119.

McCracken, K. G., and J. Beer (2007), Long-term changes in the cosmic ray intensity at Earth, 1428–2005, *J. Geophys. Res.*, *112*, A10101, doi:10.1029/2006JA012117.

McCracken, K. G., F. B. McDonald, J. Beer, G. Raisbeck, and F. Yiou (2004), A phenomenological study of the long-term cosmic ray modulation, 850–1958 AD, *J. Geophys. Res.*, *109*, A12103, doi:10.1029/2004JA010685.

Neff, U., S. J. Burns, A. Mangini, M. Mudelsee, D. Fleitmann, and A. Matter (2001), Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago, *Nature*, *411*, 290–293.

Parker, E. N. (1958), Dynamics of the interplanetary gas and magnetic fields, *Astrophys. J.*, *128*, 664.

Rouillard, A. P., and M. Lockwood (2007), Centennial changes in solar activity and the response of galactic cosmic rays, *Adv. Space Res.*, *40*, 1078–1086, doi:10.1016/j.asr.2007.02.096.

Rouillard, A. P., M. Lockwood, and I. Finch (2007), Centennial changes in the solar wind speed and in the open solar flux, *J. Geophys. Res.*, *112*, A05103, doi:10.1029/2006JA012130.

Solanki, S. K., M. Schüssler, and M. Fligge (2000), Evolution of the Sun's large-scale magnetic field since the Maunder minimum, *Nature*, *408*, 445–447, doi:10.1038/35044027.

Steinhilber, F., J. A. Abreu, and J. Beer (2008), Solar modulation during the Holocene, *Astrophys. Space Sci. Trans.*, *4*, 1–6.

Steinhilber, F., et al. (2009), Interplanetary magnetic field during the past 9,300 years inferred from cosmogenic radionuclides, *J. Geophys. Res.*, doi:10.1029/2009JA014193, in press.

Tapping, K. F., D. Boteler, P. Charbonneau, A. Crouch, A. Manson, and H. Paquette (2007), Solar magnetic activity and total irradiance since the Maunder Minimum, *Sol. Phys.*, *246*, 309–326, doi:10.1007/s11207-007-9047-x.

Usoskin, I. G., K. Alanko-Huotari, G. A. Kovaltsov, and K. Mursula (2005), Heliospheric modulation of cosmic rays: Monthly reconstruction for 1951–2004, *J. Geophys. Res.*, *110*, A12108, doi:10.1029/2005JA011250.

Vonmoos, M., J. Beer, and R. Muscheler (2006), Large variations in Holocene solar activity: Constraints from ^{10}Be in the Greenland Ice Core Project ice core, *J. Geophys. Res.*, *111*, A10105, doi:10.1029/2005JA011500.

Wang, Y.-M., J. L. Lean, and N. R. Sheeley Jr. (2005), Modeling the Sun's magnetic field and irradiance since 1713, *Astrophys. J.*, *625*, 522–538, doi:10.1086/429689.

Wanner, H., et al. (2008), Mid- to Late Holocene climate change: An overview, *Quat. Sci. Rev.*, *27*, 1791–1828, doi:10.1016/j.quascirev.2008.06.013.

J. Beer and F. Steinhilber, Swiss Federal Institute of Aquatic Science and Technology, Überlandstrasse 133, CH-8600 Dübendorf, Switzerland. (friedhelm.steinhilber@eawag.ch)

C. Fröhlich, Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, CH-7260 Davos Dorf, Switzerland.