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# Solar cycle 24: Implications for energetic particles and long-term space climate change

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[1] The recent solar minimum was the longest and deepest of the space age, with the lowest average sunspot numbers for nearly a century. The Sun appears to be exiting a grand solar maximum (GSM) of activity which has persisted throughout the space age, and is headed into a significantly quieter period. Indeed, initial observations of solar cycle 24 (SC24) continue to show a relatively low heliospheric magnetic field strength and sunspot number ($R$), despite the average latitude of sunspots and the inclination of the heliospheric current sheet showing the rise to solar maximum is well underway. We extrapolate the available SC24 observations forward in time by assuming $R$ will continue to follow a similar form to previous cycles, despite the end of the GSM, and predict a very weak cycle 24, with $R$ peaking at ~65–75 around the middle/end of 2012. Similarly, we estimate the heliospheric magnetic field strength will peak around 6nT. We estimate that average galactic cosmic ray fluxes above 1GV rigidity will be ~10% higher in SC24 than SC23 and that the probability of a large SEP event during this cycle is 0.8, compared to 0.5 for SC23. Comparison of the SC24 $R$ estimates with previous ends of GSMs inferred from 9300 years of cosmogenic isotope data places the current evolution of the Sun and heliosphere in the lowest 5% of cases, suggesting Maunder Minimum conditions are likely within the next 40 years. **Citation:** Owens, M. J., M. Lockwood, L. Barnard, and C. J. Davis (2011), Solar cycle 24: Implications for energetic particles and long-term space climate change, *Geophys. Res. Lett.*, *38*, L19106, doi:10.1029/2011GL049328.

## 1. Introduction

[2] The recent solar minimum, the end of solar cycle 23 (SC23), has been longest and deepest of the space age, with the weakest heliospheric magnetic field, $B$ [*Lockwood et al.*, 2009a, 2009b] and a significant reduction in the solar wind speed and density [*McComas et al.*, 2008]. At the photosphere, this minimum has resulted in the largest number of consecutive sunspot-free days since 1913 and the lowest polar magnetic field strength since routine observations began in 1975 [*Wang et al.*, 2009]. The magnitude of the delayed cycle 24 is of major interest not only for space weather concerns during the remainder of SC24 [e.g., *Barnard and Lockwood*, 2011; *McCracken*, 2007; *Hapgood*, 2011], but also long-term space climate change [*Barnard et al.*, 2011].

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[3] Average solar activity, as quantified by a variety of parameters, has been declining since about 1985 [*Lockwood and Fröhlich*, 2007] and the recent exceptionally low minimum is part of this decline [*Lockwood*, 2010]. From a study of the durations of Grand Solar Maxima (GSMs) during the past 9300 years, as detected in cosmogenic isotope data, *Abreu et al.* [2008] deduced that the current GSM was uniquely long-lived and due to end soon. This was supported by extrapolations of recent trends in heliospheric parameters [e.g., *Lockwood et al.*, 2009b]. This decline has potential implications for predictions of winter climate in Europe [*Lockwood et al.*, 2011] and of hazardous particles in Earth environments [*McCracken*, 2007; *Barnard et al.*, 2011], specifically galactic cosmic rays (GCRs) and solar energetic particles (SEPs).

[4] In Section 2, we extrapolate the current observations of SC24 to estimate the likely sunspot number, $R$, at the next solar maximum. In Section 3 we perform a similar analysis for the heliospheric magnetic field strength and galactic cosmic ray intensity as measured by a neutron monitor, which are used to estimate the energetic particle environment for SC24. Section 4 uses the estimate of $R$ for SC24 to estimate the likely long-term solar variations.

## 2. Predicting Solar Cycle 24

[5] Figure 1 shows time series of various solar parameters since 1975, when routine photospheric magnetic field measurements began. All data have been averaged to 27 days. Observed monthly sunspot number ($R$) is shown in blue: The peak amplitude of $R$ has been declining through much of the space age [*Lockwood et al.*, 2009b; *Lockwood and Fröhlich*, 2007], and the recent solar minimum was particularly low, with $R$ essentially zero for much of 2009. The black line shows the average latitude ($\theta$, in degrees) of sunspots, scaled up by a factor 5: The sudden increase at solar minimum is due to the emergence of high latitude sunspot pairs of new cycle polarity, which results in the classic butterfly diagram. The red line shows the HCS inclination index $i$ (which is the HCS length perpendicular to the solar rotation direction [*Owens et al.*, 2011]), computed from potential-field source-surface reconstructions of Wilcox Solar Observatory magnetograms: this has been scaled by 1800 to fit on the same y-axis scale.

[6] While $R$ is a good proxy for the rate of photospheric flux emergence and hence the production of new open solar flux [e.g., *Solanki et al.*, 2000; *Vieira and Solanki*, 2010; *Krivova et al.*, 2007], $i$ may serve as an indicator of the rate at which open solar flux is destroyed [*Sheeley et al.*, 2001; *Owens et al.*, 2011]. Indeed, the HCS did not flatten as quickly at the end of cycle 23, which may be responsible for the associated drop in $B$ in the recent solar minimum [*Owens et al.*, 2011].

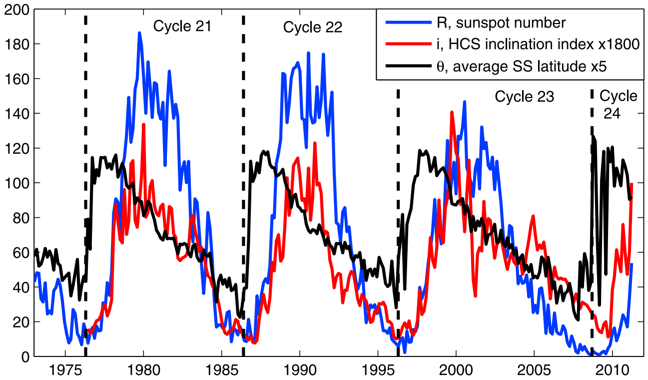


**Figure 1.** Solar parameters over the last 35 years. The blue line shows the monthly sunspot number, $R$, the black line is the average sunspot latitude, $\theta$, scaled up by a factor 5 for comparison. The jump in latitude from ~10° to ~25° is used to define the start of a new cycle, shown as vertical dashed lines. The red line shows the HCS inclination index, $i$, times a scaling factor of 1800. In general, the solar cycle variations in $i$ and $a$ are quite similar, particularly during the rise phase, despite the marked difference in the magnitudes of $R$.

[7] Using the minimum value of $R$ to precisely define the start/end of solar cycles can result in some ambiguity, particularly during the recent minimum when $R$ remained near zero for nearly two years. But the behaviour in $\theta$ and $i$ is remarkably similar from cycle to cycle, particularly during the rising phase, despite the variation in peak $R$ (note, however, the increased noise during the 2009-2010 rise due to near-zero $R$, and hence the emergence/decay of individual spots having a much larger effect on $\theta$ than during previous minima). Thus we use the sharp increase in $\theta$ to define the start of a new cycle, shown as the dashed vertical lines in Figure 1. See also Table 1. Using this as $t = 0$, Figure 2 (top) compares the previous three solar cycles (coloured lines) with the start of cycle 24 (thick black line). Figure 2 (top left) highlights the similarity in $\theta$ between cycles, except for the initial noise in the rise for SC24 (discussed above) and the increased length of SC23. Figure 2 (top middle) shows that for all four cycles, the inclination of the HCS increases sharply approximately 1 year after the $\theta$ increase, coinciding with the start of the linear decline in $\theta$. Figure 2 (top right) shows that $R$ is significantly lower thus far in SC24.

[8] Figure 2 (bottom) shows a comparison of SC24 with cycles 12 through 23 (i.e., those cycles for which sunspot latitude data are available). Note the reduced time interval shown compared to Figure 2 (top), as we are interested only in the rise to maximum. The red line and pink-shaded area in Figure 2 (bottom left) shows a composite of the mean and standard deviation, respectively, of $\theta$ over cycles 12–23, using the epoch times listed in Table 1. Figure 2 (bottom middle) shows the same analysis for $R$. The thicker pink-shaded area clearly indicates far more cycle-to-cycle variability in $R$ than $\theta$, and the SC24 variation in $R$ deviates significantly from the average behaviour. We therefore scale cycles 12 to 23 to the average variation in $R$: For cycle $X$, we find the linear scaling factor, $\alpha$, which results in the minimum value of $|R_X - \alpha\langle R\rangle|$ during the rise phase of the cycle (taken to be t = 1 to t = 4). Results are listed in Table 1. By further scaling this composite to the available data for cycle 24, we produce the prediction for cycle 24 shown in Figure 2 (bottom right). Despite the end of the current GSM it is necessary to assume that cycle 24 will continue to follow the average solar cycle behaviour over SC12-23. $R$ is expected to peak around 65 ± 10 about the middle/end of 2012. This is slightly lower than NOAA's most recent expert-panel prediction of $R = 90$ around the middle of 2013 (http://www.swpc.noaa.gov/SolarCycle/SC24/index.html, see also *Pesnell* [2008] for a summary of the wide range of SC24 predictions), but comparable to estimates of 75 ± 8 based on polar field observations [*Svalgaard et al.*, 2005].

## 3. Implications for Energetic Particles

[9] We now apply the same composite scaling procedure to the space-age observations of heliospheric magnetic field strength, $B$, total unsigned heliospheric magnetic flux, $F$, and neutron monitor counting rate, $N$. We note that all the space-age cycles have all been part of a Grand Solar Maximum, whereas SC24 is predicted to return to lower, more nominal activity levels. Thus we have to assume, without any direct observations, that the heliospheric properties of SC24 follow the same statistical behaviour as the previous GSM cycles. The red lines in Figure 3 (left) show the variations in $B$, $F$ and $N$ over SC20-23 using OMNI data [*King and Papitashvili*, 2005] and neutron monitor counting rate, in 100s counts per hour, from the McMurdo station in Antarctica, compositing both odd and even solar magnetic polarity cycles [e.g., *Usoskin*, 2008, and references therein]. These are then scaled to the mean values using the factors shown in Table 1. Figure 3 (right) shows the mean-scaled variation further linearly adjusted to the available SC24 observations, shown in black. $B$ is expected to peak at the start of 2014 at around 6 nT, while $F$ should peak around $8 \times 10^{14}$ Wb. Neutron monitor counting rates at McMurdo should stay above 9000 throughout the cycle. This results in a GCR intensity ~10% higher in SC24 than SC23.

[10] *Barnard and Lockwood* [2011] and *Barnard et al.* [2011] used space-age data to characterise GCR flux (of rigidity > 1 GV), $I_{>1GV}$, and the probability of large SEP events (integrated event fluence of >30 MeV particles exceeding $5 \times 10^9 \text{cm}^{-2}$), $P_{SEP}$, in terms of $B$ and $R$. Using our SC24 $B$ and $R$ predictions, we find an increase in $I_{>1GV}$ similar to the predicted neutron monitor counting rate change (~10%

**Table 1.** The Epoch Times for the Start of Solar Cycles 12–24, Defined Using the Sharp Increase in Average Sunspot Latitude and Scaling Factors $\alpha$ to Yield the Average Value of Sunspot Number, $R$, IMF Strength at 1AU, $B$, Total Heliospheric Flux, $F$ and Neutron Monitor Counting Rates, $N$

| Cycle | Start Year | Scaling Factors, $\alpha$ | | | |
|---|---|---|---|---|---|
| | | $R$ | $B$ | $F$ | $N$ |
| 12 | 1879.2 | 0.63 | - | - | - |
| 13 | 1889.5 | 0.71 | - | - | - |
| 14 | 1901.6 | 0.45 | - | - | - |
| 15 | 1913.7 | 0.83 | - | - | - |
| 16 | 1923.5 | 0.67 | - | - | - |
| 17 | 1934.0 | 1.00 | - | - | - |
| 18 | 1944.3 | 1.25 | - | - | - |
| 19 | 1954.3 | 1.67 | - | - | - |
| 20 | 1964.5 | 0.91 | 0.86 | 0.89 | 1.02 |
| 21 | 1976.6 | 1.43 | 1.00 | 0.98 | 1.01 |
| 22 | 1986.7 | 1.67 | 1.09 | 1.16 | 0.95 |
| 23 | 1996.8 | 1.11 | 1.01 | 0.98 | 1.02 |
| 24 | 2009.2 | 0.55 | 0.75 | 0.70 | 1.07 |

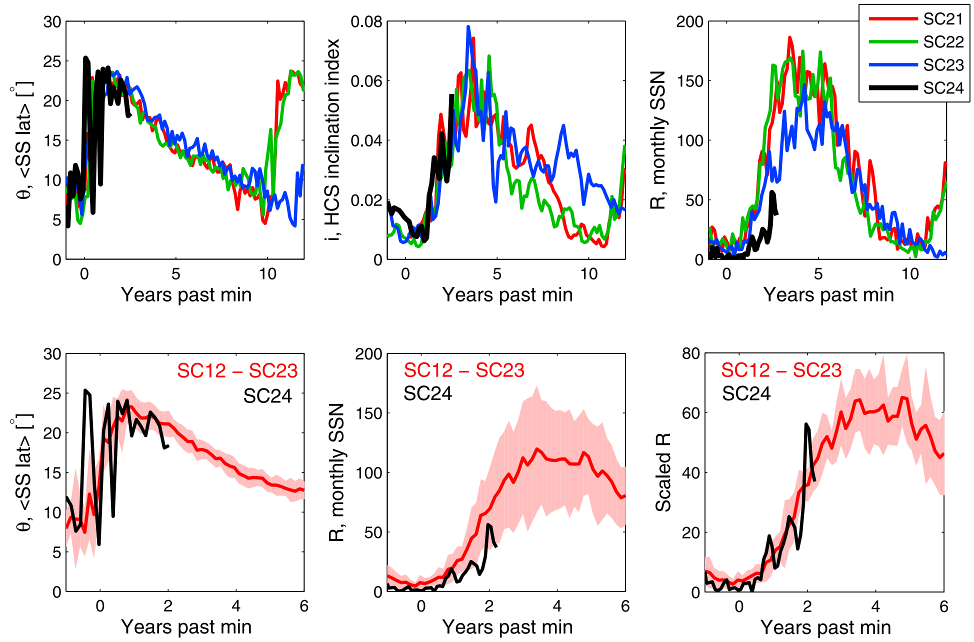


**Figure 2.** A comparison of solar cycle 24 (black), with SC21-23 (coloured lines). The variation in (top left) the average sunspot latitude and (top middle) the HCS inclination is very similar for the rise phase of all four cycles, despite (top right) the large difference in sunspot number between cycles. A comparison of SC24 with a composite of (bottom left) $\theta$ and (bottom middle) $R$ for SC12 through SC23. (bottom right) A linear scaling of $R$ used to predict a maximum R for SC24 of 65-75 around the end of 2012.

higher than SC23). Using observed values of $B$ and $R$, we find that the integrated value of $P_{SEP}$ for SC23 (from minimum to minimum) was 0.5, whereas the predictions for SC24 yield 0.8. Thus a large SEP event is 60% more likely during the current solar cycle than it was in the previous one. This is due to the predicted $B$ decease, which reduces heliospheric Alfven speed, increasing the shock strength. We note, however, that such low values of $B$ are outside the range used to empirically characterise the $P_{SEP}$ algorithm and that additional factors may become important in this new parameter regime. Additionally, the occurrence of moderate SEP events is likely to decline with the weaker solar activity cycle [*Barnard and Lockwood*, 2011; *Barnard et al.*, 2011].

## 4. Implications for Long-Term Solar Variability

[11] Assuming SC24 continues to follow the average $R$ variation from SC12-23 and peaks around $R = 65 - 75$, then the end of the space-age grand solar maximum (GSM) occurred during the recent minimum [*Usoskin et al.*, 2003; *Solanki et al.*, 2004; *Abreu et al.*, 2008]. Using $^{10}$Be cosmogenic isotope data, extended to overlap with modern neutron monitor data by means of the heliospheric modulation formalism [*Steinhilber et al.*, 2008, 2010], *Barnard et al.* [2011] characterised solar activity following the end of 24 GSMs which occurred over the last 9300 years [*Lockwood*, 2010; *Lockwood et al.*, 2011]. However, note that $^{14}$C data only show 19 GSMs during a similar time period [e.g., *Usoskin*, 2008, and references therein]. Two of the 24 $^{10}$Be GSM ends resulted in Maunder minimum-like conditions within 40 years. Lacking information about the magnitude of cycle 24, *Barnard et al.* [2011] concluded there is an 8% probability of Maunder minimum-like conditions within the next 40 years. Here, we use our estimate

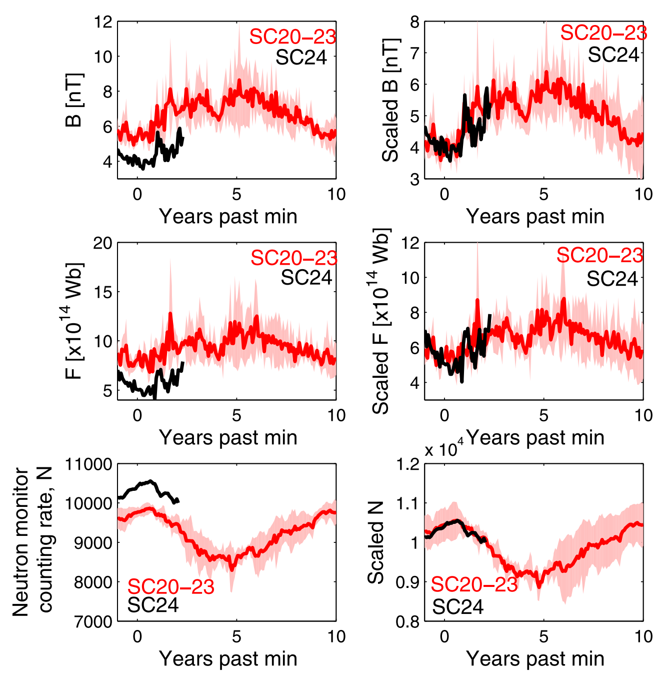


**Figure 3.** (left) A comparison of the heliospheric magnetic field strength, $B$, the total heliospheric magnetic flux, $F$ and the neutron count at McMurdo in Antarctica, $N$ for solar cycle 24 (black) with SC20-23 (red). (right) SC20-23 scaled to the average, then to SC24 levels. $B$ is expected to peak at the start of 2014 at around 6 nT, while $F$ should peak around $8 \times 10^{14}$ Wb. Neutron counts at McMurdo should stay above 9000 throughout the cycle, approximately 10% higher than SC23.

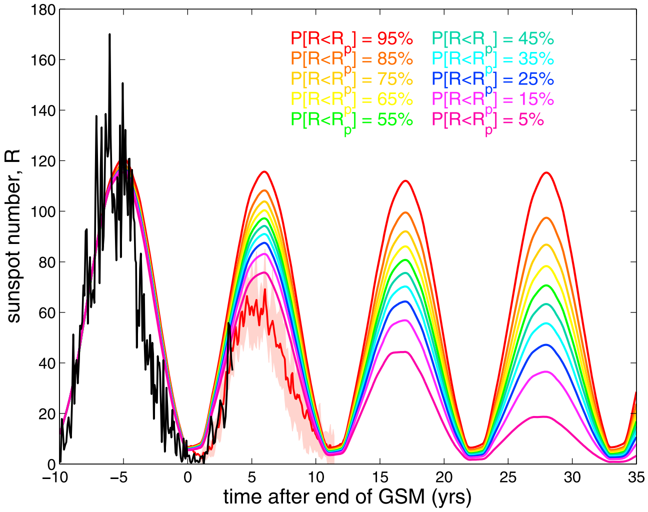


**Figure 4.** Past and future variations in *R*. Coloured smooth curves show probabilities that sunspot number will be below a certain level following the exit from a GSM, based on the previous 24 GSM endings analysed by *Barnard et al.* [2011]. These probabilities are in 10% intervals starting at 5% in mauve, to 95% in red. The black plot shows the observed sunspot number, which transitions to the red prediction for cycle 24. If this SC24 extrapolation is correct, this GSM end is in the lowest 5% in terms of *R*.

for SC24 to better constrain the probability of a period of such low solar activity.

[12] Figure 4 shows past and future variations in *R*. Coloured smooth curves show the values $R_p$ that *R* will fall below at certain probability levels $P_{[R<Rp]}$ following the exit from a GSM, based on the previous 24 GSM endings [*Barnard et al.*, 2011] and assuming all cycles will be 11 years in duration. These probabilities are in 10% intervals starting at 5% in mauve, to 95% in red. The black plot shows the observed sunspot number, transitioning to the red prediction for cycle 24. If this SC24 extrapolation is correct, the current GSM end is in the lowest 5%, suggesting the Sun is on course for a new Maunder minimum within the next 40 years. Using the higher NOAA prediction of $R \sim 90$ still puts the SC24 in the lowest 35% of GSM endings.

## 5. Discussion and Conclusions

[13] While peak sunspot number varies considerably from cycle to cycle, the distribution of photospheric magnetic flux, manifest in the average latitude of sunspots (12 solar cycles of data available) and the heliospheric current sheet inclination (only 3 cycles of data available), is remarkably similar during the rise phase of different solar cycles. Defining the start of a solar cycle as the time of the sharp increase in average sunspot latitude allows cycles to be composited to describe an "average" cycle. Linearly scaling all cycles to this average, then further scaling to the available cycle 24 observations gives a prediction of sunspot variation for cycle 24, assuming it continues to follow the average variation. In this manner, we predict the Sun will reach a sunspot maximum of $R \sim 65 - 75$ around the middle/end of 2012. This is lower than the official NOAA prediction of $R \sim 90$ at the middle of 2013.

[14] We performed a similar solar cycle scaling analysis for the heliospheric magnetic field strength, *B*, the total unsigned heliospheric magnetic flux, *F*, and ground-based neutron monitor counting rates, *N*. The uncertainties in these SC24 estimates are higher than for *R*, as data are only available for space-age solar cycles. We predict *B* to peak around 6 ± 1 nT, roughly equal to average minimum conditions over SC20-23, and about a third to a quarter lower than the average maximum value during that interval. *F* shows very similar trends. The probability of a major SEP event is 60% higher during the current SC than it was during the last one and the GCR flux above 1GV is ~10% higher.

[15] Past work has used cosmogenic isotope data to predict the future evolution of solar activity at various levels of probability based on the ends of past grand solar maxima [*Barnard et al.*, 2011; *Lockwood et al.*, 2011]. In the current paper we have taken this further by studying the evolution of several solar and heliospheric parameters during the current solar cycle and found that they are following trajectories consistent with a rapid descent into Maunder minimum conditions (within about 40 years). However, it must be stressed that this is not based on modelling of the solar dynamo, rather it uses past experience which also shows that declines from one cycle to the next do not always persist. For example, one might have reached the same conclusion when cycle 20 was found to be so much weaker than the exceptional cycle 19 before it; but that trend did not persist, with long-term solar activity rising again to a second peak in the middle of cycle 22 [*Lockwood and Fröhlich*, 2007; *Lockwood et al.*, 2011]. However, that reversal of the initial decline also resulted in the current grand solar maximum becoming the longest in the 9300-year record [*Usoskin et al.*, 2003; *Solanki et al.*, 2004; *Abreu et al.*, 2008] and that may be related to the unusually rapid descent that is now taking place.

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## References

Abreu, J. A., J. Beer, F. Steinhilber, S. M. Tobias, and N. O. Weiss (2008), For how long will the current grand maximum of solar activity persist?, *Geophys. Res. Lett.*, *35*, L20109, doi:10.1029/2008GL035442.

Barnard, L., and M. Lockwood (2011), A survey of gradual solar energetic particle events, *J. Geophys. Res.*, *116*, A05103, doi:10.1029/2010JA016133.

Barnard, L., M. Lockwood, M. A. Hapgood, M. J. Owens, C. J. Davis, and F. Steinhilber (2011), Predicting space climate change, *Geophys. Res. Lett.*, *38*, L16103, doi:10.1029/2011GL048489.

Hapgood, M. A. (2011), Towards a scientific understanding of the risk from extreme space weather, *Adv. Space Res.*, *47*, 2059–2072.

King, J. H., and N. E. Papitashvili (2005), Solar wind spatial scales in and comparisons of hourly Wind and ACE plasma and magnetic field data, *J. Geophys. Res.*, *110*, A02104, doi:10.1029/2004JA010649.

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.

Lockwood, M. (2010), Solar change and climate: An update in the light of the current exceptional solar minimum, *Proc. R. Soc. A*, *466*, 303–329, doi:10.1098/rspa.2009.0519.

Lockwood, M., and C. Fröhlich (2007), Recent oppositely directed trends in solar climate forcings and the global mean surface air temperature, *Proc. R. Soc. A*, *463*, 2447–2460, doi:10.1098/rspa.2007.1880.

Lockwood, M., M. Owens, and A. P. Rouillard (2009a), Excess open solar magnetic flux from satellite data: 2. A survey of kinematic effects, *J. Geophys. Res.*, *114*, A11104, doi:10.1029/2009JA014450.

Lockwood, M., A. P. Rouillard, and I. D. Finch (2009b), The rise and fall of open solar flux during the current grand solar maximum, *Astrophys. J.*, *700*, 937–944, doi:10.1088/0004-637X/700/2/937.

Lockwood, M., R. G. Harrison, M. J. Owens, L. Barnard, T. Woollings, and F. Steinhilber (2011), The solar influence on the probability of relatively cold UK winters in the future, *Environ. Res. Lett.*, *6*(3), 034004, doi:10.1088/1748-9326/6/3/034004.

McComas, D. J., R. W. Ebert, H. A. Elliott, B. E. Goldstein, J. T. Gosling, N. A. Schwadron, and R. M. Skoug (2008), Weaker solar wind from the polar coronal holes and the whole Sun, *Geophys. Res. Lett.*, *35*, L18103, doi:10.1029/2008GL034896.

McCracken, K. G. (2007), Changes in the cosmic ray and heliomagnetic components of space climate, 1428–2005, including the variable occurrence of solar energetic particle events, *Adv. Space Res.*, *40*, 1070–1077, doi:10.1016/j.asr.2007.01.080.

Owens, M. J., N. U. Crooker, and M. Lockwood (2011), How is open solar magnetic flux lost over the solar cycle?, *J. Geophys. Res.*, *116*, A04111, doi:10.1029/2010JA016039.

Pesnell, W. D. (2008), Predictions of solar cycle 24, *Sol. Phys.*, *252*, 209–220, doi:10.1007/s11207-008-9252-2.

Sheeley, N. R., Jr., T. N. Knudson, and Y.-M. Wang (2001), Coronal inflows and the Sun's nonaxisymmetric open flux, *Astrophys. J. Lett.*, *546*, 131–135.

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.

Solanki, S. K., I. G. Usoskin, B. Kromer, M. Schüssler, and J. Beer (2004), Unusual activity of the Sun during recent decades compared to the previous 11,000 years, *Nature*, *431*, 1084–1087, doi:10.1038/nature02995.

Steinhilber, F., J. A. Abreu, and J. Beer (2008), Solar modulation during the Holocene, *Astrophys. Space Sci. Trans.*, *4*, 1–6, doi:10.5194/astra-4-1-2008.

Steinhilber, F., J. A. Abreu, J. Beer, and K. G. McCracken (2010), Interplanetary magnetic field during the past 9300 years inferred from cosmogenic radionuclides, *J. Geophys. Res.*, *115*, A01104, doi:10.1029/2009JA014193.

Svalgaard, L., E. W. Cliver, and Y. Kamide (2005), Sunspot cycle 24: Smallest cycle in 100 years?, *Geophys. Res. Lett.*, *32*, L01104, doi:10.1029/2004GL021664.

Usoskin, I. G. (2008), A history of solar activity over millennia, *Living Rev. Sol. Phys.*, *5*, 3.

Usoskin, I. G., S. K. Solanki, M. Schüssler, K. Mursula, and K. Alanko (2003), Millennium-scale sunspot number reconstruction: Evidence for an unusually active Sun since the 1940s, *Phys. Rev. Lett.*, *91*(21), 211101, doi:10.1103/PhysRevLett.91.211101.

Vieira, L. E. A., and S. K. Solanki (2010), Evolution of the solar magnetic flux on time scales of years to millenia, *Astron. Astrophys.*, *509*, A100, doi:10.1051/0004-6361/200913276.

Wang, Y.-M., E. Robbrecht, and N. R. Sheeley Jr. (2009), On the weakening of the polar magnetic fields during solar cycle 23, *Astrophys. J.*, *707*, 1372–1386, doi:10.1088/0004-637X/707/2/1372.

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