CrossMark

Salient Features of the New Sunspot Number Time Series

H.S. Ahluwalia[1] · R.C. Ygbuhay[1]

Abstract Recently Clette *et al.* (Space Sci. Rev. **186**, 35, 2014) completed the first revision of the international sunspot number SSN(V2) since its creation by Wolf in 1849 SSN(V1) starting in 1700 and ending in May 2015. The yearly values of SSN(V2) are larger than those of SSN(V1) but the secular trend in their timelines both exhibit a gradual descent after Cycle 21 minimum resulting in greatly reduced activity for Cycle 24. It has two peaks; one in 2012 due to activity in the north hemisphere (NH) and the other in 2014 due to excess activity in the south hemisphere (SH). The N–S excess of hemispheric SSNs is examined for 1950 – 2014, in relation to the time variations of the solar polar field for 1976 – 2015, covering five complete solar cycles (19 – 23) and parts of the bordering two (18, 24). We find that SH tends to become progressively more active in the declining phase of the cycles reaching an extreme value that gave rise to a second higher peak in October 2014 in the smoothed SSNs accompanied by a strong solar polar field in SH. There may be a Gleissberg cyclicity in the asymmetric solar dynamo operation. The continuing descent of the secular trend in SSNs implies that we may be near a Dalton-level grand minimum. The low activity spell may last well past 2060, accompanied by a stable but reduced level of the space weather/climate. Fourier spectrum of the time domain of SSNs shows no evidence of the 208 year/cycle (ypc) (DeVries/Suess cycle) seen in the cosmogenic radionuclide (^{10}Be) concentration in the polar ice cores and ^{14}C record in trees indicating that 208 ypc peak may be of non-solar origin. It may arise from the climate process(es) that change(s) the way radionuclides are deposited on polar ice. It should be noted that we only have ∼ 400 years of SSN data, so it is possible that DeVries/Suess cycle is really driven by the Sun but for now we do not have any evidence of that; there is no known physical process linking 208 ypc to solar dynamo operation.

Keywords Sunspot numbers · Solar polar field · Planetary indices · Gleissberg cycle

✉ H.S. Ahluwalia
hsa@unm.edu

[1] Department of Physics & Astronomy, MSC07 4220, University of New Mexico, Albuquerque, NM 87131, USA

1. Introduction

The sunspot number (SSN) is regarded as the standard index of solar activity; its observational timeline extends ∼ 400 years, beginning with the telescope observation of sunspots in 1611 by Galileo Galilei (1564 – 1642). He noted that sunspots form and dissolve on the solar surface and progress across the disk indicating that the Sun rotates. Schwabe discovered the cyclic character of SSNs after a 17 yr study made public in 1843. Wolf (of Zurich) extended the sunspot number data from old records back to 1700. The average period of the Schwabe cycle is 11.2 yr, actual periods have ranged from 7 to 14 yr (Kane, 2008), this is a result based on the distance between the maxima of two consecutive sunspot cycles and this interval is slightly different when one considers the distance between two consecutive minima. Many observers worldwide now contribute to SSN data collection; see Bray and Loughhead (1965) for details of the early history, the characteristics and the research on sunspots. The series created by Wolf in 1849 (Friedli, 2016) and revised by Clette *et al.* (2014) starts in 1700. We label the former SSN(V1) with timeline ending in May 2015 and the latter SSN(V2), the data are available at WDC-SILSO, Royal Observatory of Belgium at Brussels, http://www.sidc.be/silso/datafiles. The salient features of the two timelines are compared with the long-term trends in the planetary indices aa/Ap, the north-south excess (NSE) of hemispheric SSNs, as well as the solar polar magnetic field intensity for shorter time intervals. We also use the monthly SSN data for 1749 – 2015 to obtain a Fourier spectrum. We find that the DeVries/Suess peak is absent.

2. Data Analysis

Figures 1a, b depict timelines for SSN(V1) and (V2), respectively. The annual mean values are plotted in black for 1700 – 2014 for SSN(V1), 1700 – 2015 for (V2); every fourth cycle is labeled bold. The 11-yr running mean is plotted red to indicate the secular trend in the timeline, showing that the Sun is a variable magnetic star, with phases of enhanced activity followed by those of low activity (Eddy, 1976, 1981). The grand minima are highlighted, namely the 70-yr Maunder minimum (1645 – 1715, MM) and the 40-yr Dalton minimum (1790 – 1830, DM) as well as the shallow 13-yr Gleissberg minimum (1889 – 1902, GM). The horizontal dashed lines (black) at the bottom of Figures 1a, b indicate the level of solar activity during the DM. One notes that:

- Cycle 3 is almost as active as Cycle 19 (the most active cycle ever) in SSN(V2). In fact the yearly values of SSN(V2) are larger than those of SSN(V1), the means for the covered period are 49.6, 79.5, respectively (compare scales on the y-axes) *i.e.* 60 % larger.
- Prominent features and observed trends are similar for the two timelines.
- Beginning with Cycle 10, there is a pattern where even cycles of the even–odd pairs are less active as noted by Gnevyshev and Ohl (1948); it disappears after Cycle 21. The physical process(es) leading to these solar features are not understood yet.
- The trend lines (red) indicate that the Sun entered a period of low solar activity beginning at the minimum SSN for Cycle 21, highlighted by the downward pointing arrows in Figures 1a, b. Until Cycle 23 the SSN was still above the average, but Cycle 24 is below average for both SSN(V1) and (V2). The secular trend for Cycle 24 has just reached activity levels close to those in the early 1900s. Ahluwalia and Ygbuhay (2012) suggest that we are at the advent of a Dalton-like grand minimum; Steinhilber and Beer (2013) agree with this forecast but De Jager and Duhau (2012) state that no grand minimum is
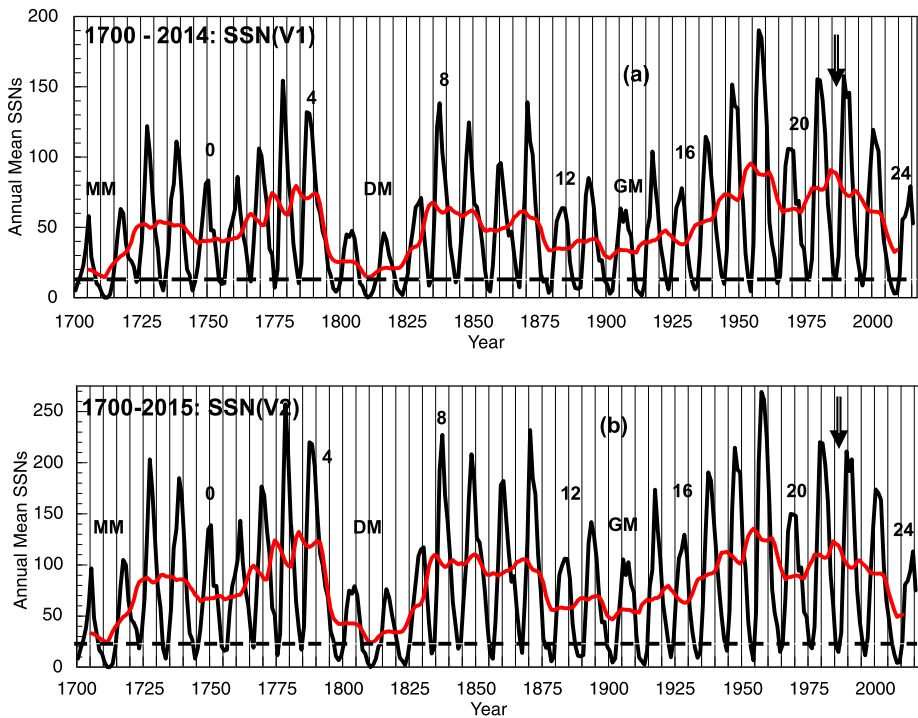
Figure 1 (a) Depicts SSN(V1) timeline and (b) applies to SSN(V2) showing the annual mean values (black) and the 11-yr running mean (red). Arrows indicate the start of the modern low-activity period; see text for details.

expected to occur during the 21st century, while Lockwood (2010) opines there is only 8 % chance of the Sun falling into a grand minimum during the next 40 years. In contrast, Zharkova *et al.* (2015) develop a model to forecast a short lived grand minimum in the northern hemisphere during Solar Cycles 26–27.

- The timeline for Cycle 24 has an unusual structure arising from a pronounced N–S asymmetry of solar dynamo operation. It has two peaks; the first in 2012 due to activity in NH and a second higher prominent peak in 2014 due to an excess activity in SH (Ahluwalia, 2016).

3. Hemispheric Sunspot Number Excess

The production of hemispheric SSNs at WDC-SILSO started on 1 January 1992. To extend the plot back in time, Frédéric Clette used sunspot group data from the Uccle station (Royal Observatory of Belgium, Brussels). He kindly sent us the data, with the following comments:

"As these values are not obtained from data of the whole WDC-SILSO observing network, the total North/South is normalized to the actual total sunspot number from WDC-SILSO. So, in this case, the North/South ratio provides an approximation of the distribution of the total number between the North and South hemispheres. Two other factors make those values less accurate before 1992:
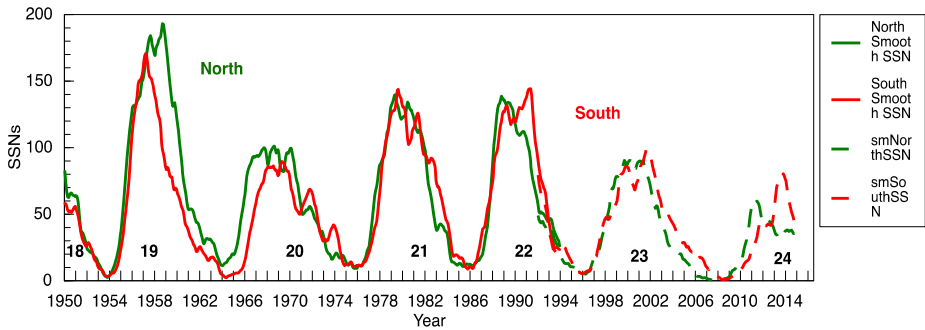
Figure 2 Figure depicts yearly smooth hemispheric SSNs for 1950–2015, north (green), south (red); solid lines till 1992 (F. Clette, private communication) and dashed lines thereafter (WDS-SILSO).

- They are based on a single station, instead of being the average of many stations.
- As one station cannot observe on all days, there are daily gaps (about 25 % of all days). This is why those hemispheric numbers are only available as monthly means. As the sampling of days inside a month is below 100 % and random, by the combination of the sampling window with the activity variations over the month, this introduces random errors on the monthly means." Still, this extension is very useful, as it doubles the time interval over which the separate behavior of both hemispheres can be reconstructed. To reduce errors further, we plot yearly smooth values of the hemispheric SSNs in Figure 2, Uccle station data are solid green lines for NH and red for SH. The corresponding data for 1992 onward are drawn as dashed lines. They cover five complete cycles (19–23) and parts of the bordering two (18, 24). The following features are noted:
- The difference between the green and red timelines gives the N–S excess (NSE) SSNs; its largest value occurs during the descent of the Cycle 19 and ascent of Cycle 20.
- There are more sunspots in NH for 1950–1970 (Cycles 18–20) and progressively excess sunspots in SH during the descent of the cycles for 1980–2010 (Cycles 21–23) more so for the Cycle 24 decay phase; also see Figures 1, 2 in Svalgaard and Kamide (2013) and Figure 2 in Ahluwalia (2015). Furthermore, Murakőzy and Ludmány (2012) analyzed the hemispheric SSN data from the Greenwich Royal Observatory for a longer period (Cycles 12–23). They find that the phase of the hemispheric cycles shows an alternating variation: NH leads in four and follows in four cycles. They note 4 + 4 cycle period is close to the Gleissberg (1939) cycle, pointing to a new aspect in the solar dynamo operation needing a long memory. Vernova, Tyasto, and Baranov (2014) argue that Cycle 24 seems to violate this rule.
- The sign of NSE changes for the descent of the following four cycles (21–24). A similar situation occurs for the SSN(V1) series (Ahluwalia, 2015). To the best of our knowledge, the physical cause(es) for NSE and its change of sign are not known. It points to our ignorance of how the solar dynamo actually works.
- SSNs declined gradually during the prolonged minimum for Cycle 23 and recovered sharply at the onset of Cycle 24.

4. Solar Polar Magnetic Field

The yearly solar polar magnetic field data for 1976–2015 are plotted in Figure 3. They are available at the Wilcox Solar Observatory (WSO) website: http://quake.stanford.edu.

Figure 3 Figure depicts polar magnetic field in the north (blue) and south (red) hemispheres along with the yearly SSN(V1) (black), vertical dashed lines are drawn through SSN maxima.
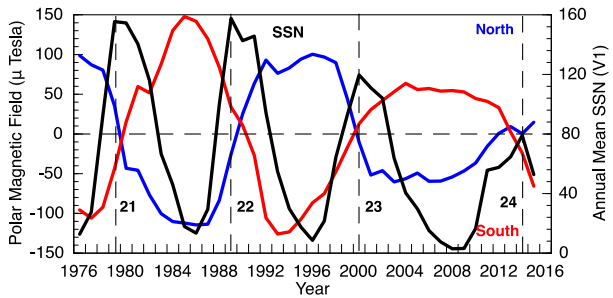
Figure 4 Figure depicts yearly Ap and SSN(V2) for 1932–2015. A three-year quasi-periodicity (TCQP) is highlighted by dashed lines.
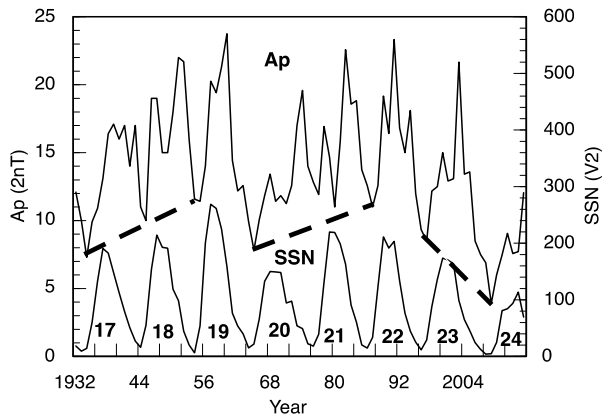

The data cover three cycles (21–23) and a part of Solar Cycle 24, yearly SSN(V1) are also plotted. The vertical dashed lines indicate an SSN maximum. The following points are noted for the limited dataset:

- The SSN minimum level gets progressively lower for Cycles 21–23 (the minimum is longer for Cycle 23) just when the Sun started transition to a lower activity state.
- Field reversals occur after the SSN maximum for Cycles 21, 22 and before the SSN maximum for Cycles 23, 24.
- The change in the polar field strength for the ascent of the even cycle, Cycle 22 (1984–1992), seems to be larger.

5. Geomagnetic Indices Ap and aa

The geomagnetic index Ap plotted in Figure 4 was designed in 1932 by Bartels (1962) to measure the geo-effectiveness of the high-speed solar wind from the coronal holes. The index has a linear scale and is derived from data at mid-latitude sites. These indices are not influenced by the climate changes on Earth. Ahluwalia (2000, 2003 and references therein) discovered a three-cycle quasi-periodicity (TCQP) in Ap and developed an empirical method to predict smooth SSN at peak (Rmax) and rise time (Tr) for a cycle, leading to a successful prediction for Cycle 23 (Kane, 2008; Petrovay, 2010). TCQP is depicted in Figure 4 for an extended period (1932–2015) along with yearly SSN(V2). The slope of TCQP in Ap becomes negative after the SSN minimum for Cycle 22. Ahluwalia and Jackiewicz (2011, 2012) – AJ12 hereafter – used the same method to predict the peak for Cycle 24 to be
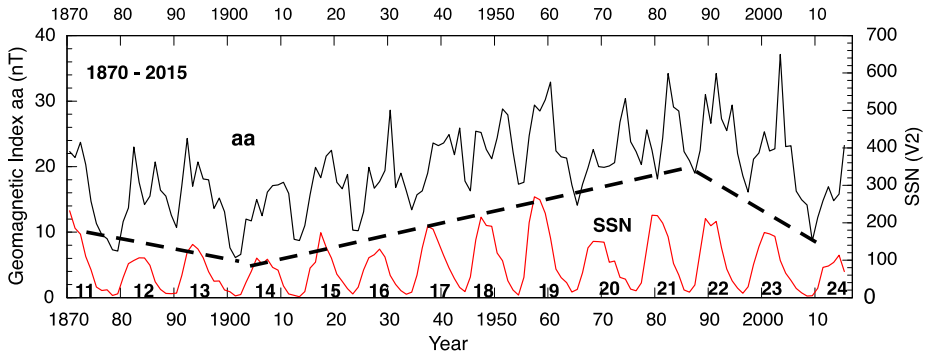
Figure 5 Figure depicts yearly values of aa index (black) and SSN(V2) (red) for 1870 – 2015.

about half of the Cycle 23 Rmax with Tr = May 2013 ± 6 month, it came very close; excess activity in SH was not anticipated by them (Ahluwalia, 2016).

Figure 5 shows a plot of the yearly values of the aa index and SSN(V2) for 1870 – 2015 for 12 cycles (12 – 23) and parts of the bordering two (11, 24); data are an updated version of a compilation by Mayaud (1972, 1973) from data obtained at two old (almost antipodal) magnetic observatories, Greenwich and Melbourne. The indices Ap and aa bear a linear correlation (Mayaud, 1980). The following points are noted:

- Beginning in 1900 an upward trend exists for TCQP in aa index for the twentieth century.
- The slope of the aa timeline changes from negative to positive near the Cycle 13 minimum in 1900 and from positive to negative near the Cycle 21 minimum as is also the case for Ap index in Figure 4, implying that a period ~ 200 year (De Vries/Suess) cycle may exist in aa/Ap indices. McCracken *et al.* (2014) analyzed paleo-cosmic ray record (^{10}Be radionuclide concentration in the polar ice cores) for 9300 years. The Fourier spectrum of the time domain of the data shows a sharp peak at 208 ypc (see their Figure 10 and Table 1). They infer that the sharpness of the spectral line suggests that this peak must originate in a mechanism associated with the solar dynamo. Peristykh and Damon (2003) stress that one should pay more attention to the 88-year Gleissberg cycle. Their analysis uses the longest ($\sim 12\,000$ years) detailed ^{14}C record in trees; it shows a sharp peak at 208 ypc (see their Figure 4) along with a prominent 104 ypc peak, ascribed by them to the second harmonic of the De Vries/Suess cycle. They show that the Gleissberg cycle is amplitude-modulated by the Suess cycle to produce 'beats' at 150 and 60 ypc. This line of reasoning is supported by an analysis of thermo-luminescence in the layers of stratified columns of sea sediments by Cini Castagnoli, Bonino, and Provenzale (1989), who infer that the observed peaks may be the result of an amplitude modulation by 206 ypc applied to those with periods of 11.4 and 82.6 years.

If one assumes that solar wind will exhibit the same periodicity for the rest of the 21st century, one should expect the next uptick of the aa/Ap timeline to occur *circa* (1986 + 88) ~ 2074. In the mean time, the indices Ap/aa may continue to undergo TCQP to a value lower than in early 1900s based on the steeper slope of the TCQP during the last few solar cycles compared to that of the period before 1900.
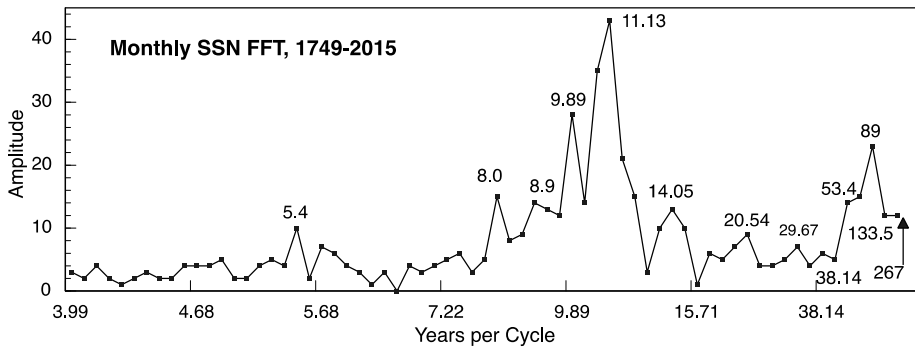
Figure 6 Figure depicts FFT derived from monthly SSN data for 1749–2015, the periods for major peaks are annotated in years.

6. SSN Fourier Spectrum

Ap is proportional to the intensity (B) of the interplanetary magnetic field (Ahluwalia, 2000). In turn, B is related to SSN (Ahluwalia, 2013) for which data are available since 1700. Therefore, a fast Fourier transform of SSN(V2) should help locate the prominent lines (periodicity, amplitude, and phase) in the SSN data corresponding to the spectral lines in B and therefore Ap; assuming that periodicities found in the past will also repeat in the 21st century. For greater resolution we use monthly SSNs for 1749–2015, the periods corresponding to major peaks are annotated in years in Figure 6 showing Fourier amplitude spectrum of SSN(V2). The following points are noted:

- Periodicities very close to those expected (Ahluwalia, 2014) are present, namely: Schwabe (11.1 ypc), Hale (20.5 ypc), TCQP (29.7 ypc), 55 ypc (Yoshimura, 1979; Silverman, 1992; Du, 2006), Gleissberg (89 ypc). The spectrum is similar to Figure 1a in Cole (1973) for a shorter period (1700–1969). The Gleissberg peak is most prominent next to the Schwabe peak in both spectra and deserves attention as stressed by Peristykh and Damon (2003).

- Several lesser peaks are also present. MacDonald (1989) argues that a large number of the observed peaks may be expressed in terms of low order integer multiples of just three frequencies chosen arbitrarily. The physical significance of this insight is not clear.

- DeVries/Suess peak (208 ypc) is absent in Figure 6 but present in McCracken *et al.* (2014) analysis of the paleo-cosmic ray record and Peristykh and Damon (2003) analysis of ^{14}C record in trees. This is also true of the MacDonald (1989) analysis of SSN Fourier spectrum, indicating that 208 ypc peak may be of non-solar origin. It may arise from climate process(es) that change(s) the way radionuclides are deposited on polar ice. It should be noted that we only have ~ 400 years of SSN data, so it is possible that this cycle is really driven by the Sun, but for now we do not have any evidence of that; there is no known physical process linking the 208 ypc peak to solar dynamo operation. This line of reasoning raises a question about the inferred secular trend in Ap/aa indices. Time will tell how the solar wind behaves for the rest of the 21st century.

7. Conclusions

The detailed study of the salient features of SSN time series revised by Clette *et al.* (2014) leads to the following conclusions.

1. The value of yearly sunspot numbers in SSN(V2) are larger than those in SSN(V1), averages for the two series are 49.6 and 79.5, respectively. But the prominent features and the observed trends are similar for the two timelines.

2. The Sun entered a period of low activity beginning at the minimum SSN for Cycle 21. The persistent downward trend after 1986 is approaching the level of the solar activity seen during the Dalton grand minimum.

3. There are more sunspots in NH for 1950–1970 (Cycles 18–20) and progressively excess sunspots in SH during the descent of the cycles for 1980–2010 (Cycles 21–23), more so for the Cycle 24 decay phase resulting in its unusual structure. This is consistent with the Murakőzy and Ludmány (2012) analysis of the hemispheric sunspot number data from the Greenwich Royal Observatory for a longer period (Cycles 12–23). They find that the phase of the hemispheric cycles shows an alternating variation: NH leads in four cycles and follows in four. They noted the $4 + 4$ cycle period is close to the Gleissberg cycle, indicating a new aspect in solar dynamo operation by implying a long memory. Vernova, Tyasto, and Baranov (2014) show that Cycle 24 seems to violate this rule.

4. The enhancement of the solar polar field in SH during Cycle 24 is unusual. The cause of the N–S asymmetry of the solar dynamo operation is unknown.

5. A periodicity of about 200 years (De Vries/Suess cycle) may exist in the planetary indices aa/Ap timeline. It is present in the radionuclide datasets extending over several millennia but not in SSN time series covering a period ~ 400 years, indicating that this periodicity may be of non-solar origin.

6. We agree with Peristykh and Damon's (2003) as well as Murakozy and Ludmány's (2012) emphasis that one should pay more attention to the Gleissberg cycle. No formal definition of the Gleissberg period exists in the literature; (90 ± 10) ypc is consistent with the values implied by different authors referenced in our discussion and those using different analytical techniques (see Frick *et al.*, 1997). The modelers should consider the possibility that the solar dynamo mechanism may have a long memory.

Disclosure of Potential Conflicts of Interest The authors declare that they have no conflicts of interest.

References

Ahluwalia, H.S.: 2000, Ap time variations and interplanetary magnetic field intensity. *J. Geophys. Res.* **105**, 27481. DOI.

Ahluwalia, H.S.: 2003, Meandering path to solar activity forecast for cycle 23. In: Velli, M., Bruno, R., Malra, F. (eds.) *Solar Wind Ten: Proc. Tenth Int. Solar Wind Conf., AIP: CP679*, 176.

Ahluwalia, H.S.: 2013, Sunspot numbers, interplanetary magnetic field, and cosmic ray intensity at Earth: nexus for the twentieth century. *Adv. Space Res.* **52**, 2112.

Ahluwalia, H.S.: 2014, An empirical approach to predicting the key parameters for a sunspot number cycle. *Adv. Space Res.* **53**, 568.

Ahluwalia, H.S.: 2015, North–South excess of hemispheric sunspot numbers and cosmic ray asymmetric solar modulation. *Adv. Space Res.* **56**, 2645.

Ahluwalia, H.S.: 2016, The descent of the solar cycle 24 and future space weather. *Adv. Space Res.* **57**, 710.

Ahluwalia, H.S., Jackiewicz, J.: 2011, Sunspot cycle 24 ascent to peak activity: a progress report. In: *Proc. 32nd Int. Cosmic Ray Conf.* **11**, 232.

Ahluwalia, H.S., Jackiewicz, J.: 2012, Sunspot cycle 23 descent to an unusual minimum and forecasts for cycle 24 activity. *Adv. Space Res.* **50**, 662.

Ahluwalia, H.S., Ygbuhay, R.C.: 2012, Sunspot cycle 24 and the advent of Dalton-like minimum. *Adv. Astron.* Article ID 126516. DOI.

Bartels, J.: 1962, *Collection of Geomagnetic Planetary Index Kp and Derived Daily Indices Ap and Cp for the Years 1932–1961*, North-Holland, New York.

Bray, R.J., Loughhead, R.E.: 1965, *Sunspots*, Barnes & Noble, New York.

Cini Castagnoli, G., Bonino, G., Provenzale, A.: 1989, The 206-year cycle in tree ring radiocarbon data and in the thermo-luminescence profile of a recent sea sediment. *J. Geophys. Res.* **94**, 11971.

Clette, F., Svalgaard, L., Vaquero, J.M., Cliver, E.W.: 2014, Revisiting the sunspot number: a 400-year perspective on the solar cycle. *Space Sci. Rev.* **186**, 35. DOI.

Cole, T.: 1973, Periodicities in solar activity. *Solar Phys.* **30**, 103.

De Jager, C., Duhau, S.: 2012, Sudden transitions and grand variations in the solar dynamo, past and future. *J. Space Weather Space Clim.* **2**, A07, 8 pp. DOI.

Du, Z.L.: 2006, A new solar activity parameter and the strength of 5-cycle periodicity. *New Astron.* **12**, 29.

Eddy, J.A.: 1976, The Maunder minimum. *Science* **192**, 1189.

Eddy, J.A.: 1981, Climate and the role of the sun. In: Rotberg, R.I. Rabb, T.K. (eds.) *Climate and History: Studies in Interdisciplinary History*, Princeton University Press, Princeton, 145.

Frick, P., Galyagin, D., Hoyt, D.V., Nesme-Ribes, E., Schatten, K.H., *et al.*: 1997, Wavelet analysis of solar activity recorded by sunspot groups. *Astron. Astrophys.* **328**, 670.

Friedli, T.K.: 2016, Sunspot Observations of Rudolf Wolf from 1849–1893. *Solar Phys.* DOI.

Gleissberg, W.: 1939, A long periodic fluctuation of the sunspot numbers. *Observatory* **62**, 158.

Gnevyshev, M.N., Ohl, A.I.: 1948, On the 22-year solar activity cycle. *Astron. Zh.* **25**, 18.

Kane, R.P.: 2008, Prediction of solar cycle 24 based on the Gnevyshev–Ohl–Kopecky rule and the three-cycle periodicity scheme. *Ann. Geophys.* **26**, 3329.

Lockwood, M.: 2010, Solar change and climate: an update in the light of the current exceptional solar minimum. *Proc. Roy. Soc. Edinb. A* **466**, 303. DOI.

MacDonald, G.J.: 1989, Spectral analysis of the time series generated by nonlinear processes. *Rev. Geophys.* **27**, 440.

Mayaud, P.N.: 1972, The aa indices: a 100 year series characterizing the magnetic activity. *J. Geophys. Res.* **77**, 6870.

Mayaud, P.N.: 1973, *A Hundred Year Series of Geomagnetic Data, 1868–1967*, IAGA Bull. **33**, Int. Union of Geod. and Geophys, Paris.

Mayaud, P.N.: 1980, *Derivation, Meaning, and Use of Geomagnetic Indices, Geophysical Monograph 22*, Am. Geophys. Union, Washington.

McCracken, K.G., Beer, J., Steinhilber, F., Abreu, J.: 2014, The heliosphere in time. *Space Sci. Rev.* **176**, 59.

Murakőzy, J., Ludmány, A.: 2012, Phase lags of solar hemispheric cycles. *Mon. Not. Roy. Astron. Soc.* **419**, 3624. DOI.

Peristykh, A.N., Damon, P.E.: 2003, Persistence of the Gleissberg 88-year cycle over the last ∼12000 years: evidence from cosmogenic isotopes. *J. Geophys. Res.* **108**, A1. 15 pp.

Petrovay, K.: 2010, Solar cycle prediction. *Living Rev. Solar Phys.* **7**, 5.

Silverman, S.M.: 1992, Secular variation of the aurora for the past 500 years. *Rev. Geophys.* **30**, 333.

Steinhilber, F., Beer, J.: 2013, Prediction of solar activity for the next 500 years. *J. Geophys. Res.* **118**, 1861.

Svalgaard, Y., Kamide, Y.: 2013, Asymmetric solar polar field reversals. *Astrophys J.* 763(1). Article id. 23, 6 pp.

Vernova, E.S., Tyasto, M.I., Baranov, D.G.: 2014, Photospheric magnetic field: relationship between North–South asymmetry and flux imbalance. *Solar Phys.* **289**, 2845.

Yoshimura, H.: 1979, The solar cycle period-amplitude relation as evidence of hysteresis of the solar cycle magnetic oscillation and the long-term (55 year) cyclic modulation. *Astrophys. J.* **227**, 1047.

Zharkova, V.V., Shepherd, S.J., Popova, E., Zharkov, S.I.: 2015, Heartbeat of the sun from principal component analysis and prediction of solar activity on a millennium timescale. *Sci. Rep.* **5**, 15689. DOI.