# Modern grand solar minimum and its impact on the terrestrial environment

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**Abstract**

The recent progress with understanding a role of the solar background magnetic field in defining solar and with quantifying the observed magnitudes of magnetic field at different times activity enable reliable long-term prediction of solar activity on a millennium timescale. This approach revealed a presence of not only 11 year solar cycles but also of grand solar cycles with duration of 330-380 years. We demonstrated that these grand cycles are formed by the interferences of two magnetic waves produced by solar dynamo in two layers of the solar interior with close but not equal frequencies. These grand cycles are always separated by grand solar minima of Maunder minimum type, with the modern GSM started in 2020 and to last until 2053. This GSM will lead to a reduction of solar irradiance by about 0.22% from the modern level and a decrease of the average terrestrial temperature by about 1.0C. The reduction of a terrestrial temperature can have important implications for different parts of the planet on growing vegetation, agriculture, food supplies and heating needs in both Northern and Southern hemispheres.

## Solar activity via summary curves of the eigen vectors of solar background magnetic field

In this article I demonstrate the properties of a new solar activity proxy – a summary curve of the eigen vectors of the solar background magnetic field (SBMF) measured from the full disk low resolution synoptic maps of Wilcox Solar Observatory, Stanford US (Zharkova et al, 2015, SC) (see Fig.1). I show that the Sun produces the eigen vectors, or magnetic dynamo waves defining its own oscillations in pairs: the largest two magnetic waves called principal components (Fig. 1, left plot), generated by a dipole magnetic field and covering 39% of total data variance. The modulus summary curve is generated from these two eigen vectors reproduce general trend of solar activity defined by averaged sunspot numbers (Fig.1, right plot) (Zharkova and Shepherd, 2022) confirming the summary curve as additional proxy of solar activity.

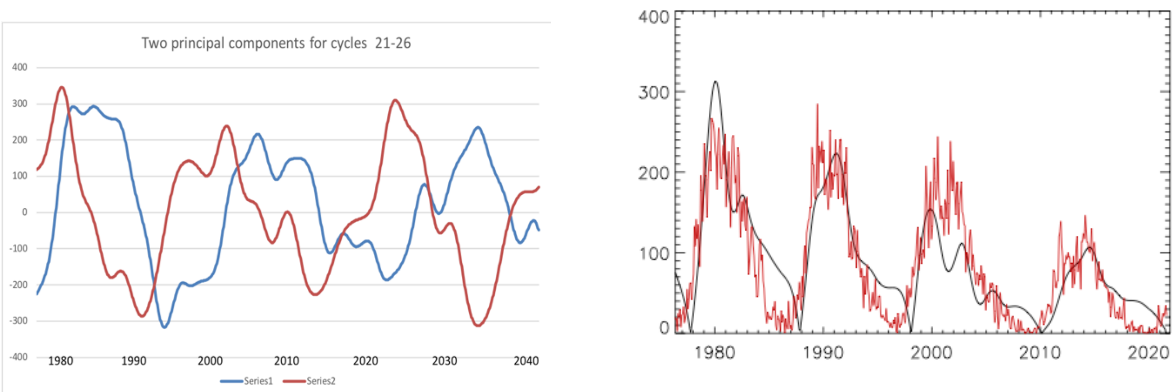


**Figure 1**. Left plot: two principal components (PCs) of solar background magnetic field (blue and green curves, arbitrary numbers) obtained for cycles 21–23 (historic data) and predicted for cycles 24–26 using the mathematical formulae derived from the historical data (from the data by Zharkova et al., 2015). Right plot: The modulus summary curve derived from the two PCs above for the 'historical' data (cycles 21–24) and compared with the averaged sunspot number (from the data by Zharkova and Shepherd, 2022).

Zharkova et al, 2015 managed to derive analytical trigonometric expressions for these two eigen vectors and expanded the summary curve to 2000 years from 1200 to 3200 shown in Fig. 2. This summary curve reveals the grand solar cycle of solar activity of 330-380 years imposed by the interference of two magnetic waves generated by dipole magnetic sources. This interference demonstrates the occurrence of grand solar minima (GSMs) between each grand solar cycles. The previous grand solar minimum was Maunder minimum (1645-1710), and the other one before named Wolf minimum (1270-1350). As seen in Figure 2 from prediction by Zharkova et al. (2015), in the next 500 years there are two modern grand solar minima approaching in the Sun: the modern one in the 21st century (2020-2053) and the second one in the 24-25 centuries (2370–2415).

The summary curve of two principal components describes the magnetic waves produced by solar dynamo in poloidal magnetic field, in contrast to the sunspot index, reproducing the magnetic waves of toroidal magnetic field. By comparing the cycle durations and amplitudes between these two indices of solar activity: the modulus summary curve of eigen vectors and averaged sunspot numbers (see Fig. 3, left plot), reveals that correlation between the curves is approaching 67% for solar cycles after 1900 (see Fig. 3, right plot).

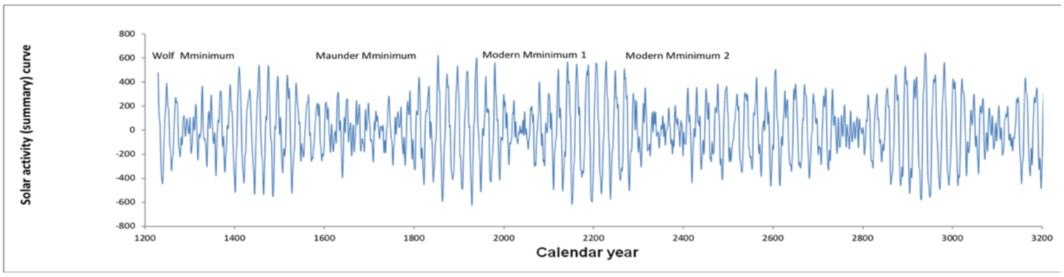


**Figure 2.** The summary curve of two eigen vectors of SBMF restored for 1200-3300 AD (built from the data obtained by Zharkova et al, 2015 revealing the previous grand solar minima (Maunder and Wolf) and predicting the modern GSM (2020-2053) with the next GSM to occur in 2375-2415.

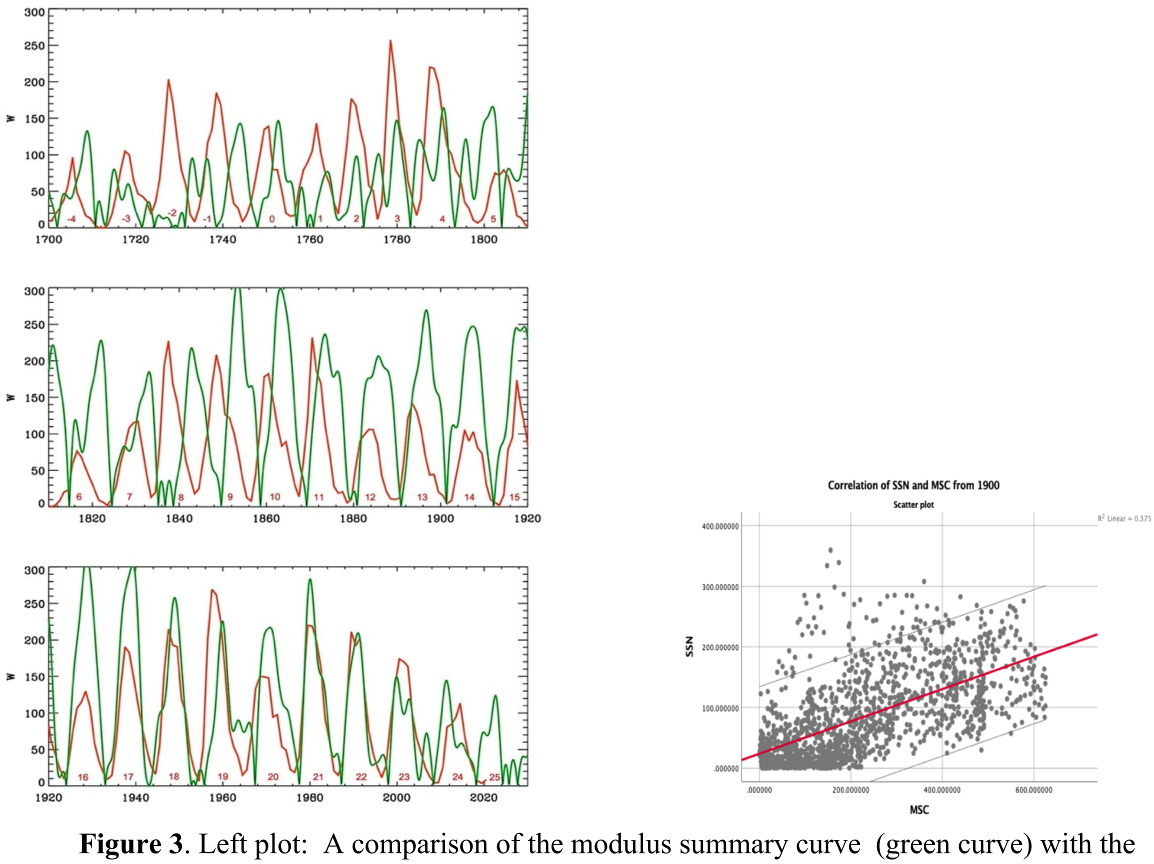


**Figure 3**. Left plot: A comparison of the modulus summary curve (green curve) with the averaged sunspot numbers (red curve) for all existing cycles. Right plot: scatter plot of the correlation (r=0.67) of the modulus summary curve with sunspot index obtained by Zharkova et al, 2023.

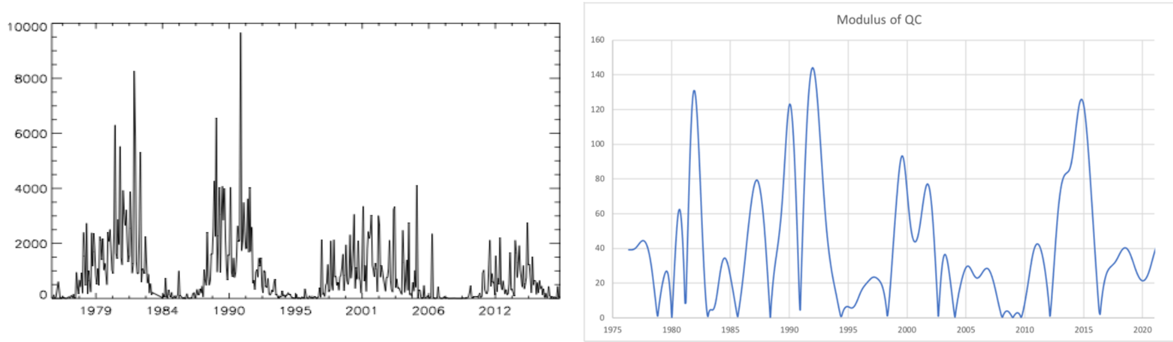


**Figure 4.** The summary curve of two eigen vectors of SBMF restored for cycles 21-24 (right plot) (Zharkova and Shepherd, 2022) versus the soft X-ray emission index of solar flares (left plot).

This high correlation is the maximum magnitude which can be achieved for the two dipole magnetic components (Zharkova et al, 2023) without adding quadruple, sextuple and octuple components.

The second pair of eigen vectors, or magnetic waves generated by quadruple magnetic sources, covering 18% of the magnetic field data variance (Fig.4, right plot) , the third pair produced by sextuple sources covering 12% of the data variance and the forth pair produced by octuple magnetic sources covering 9% of the data variance (Zharkova and Shepherd, 2022). It was shown that the modulus summary curve of eigen vectors produced by quadruple magnetic sources closely follows the soft X-ray emission index of solar flares shown in Fig. 4, left plot. This makes a perfect sense because solar flares occur from the interconnection of magnetic loops via magnetic reconnection (Zharkova et al, 2011) and, thus, often require, at least, two interacting magnetic loops, or four magnetic sources. Other eigen vectors produced by sextuple and octuple magnetic sources can define specific scenarios of the energy and jet release in the interacting magnetic loops.

**Consequence of the modern GSM for terrestrial environment**

Since the Sun has entered into the modern Grand Solar Minimum (2020-2053) this will lead to a significant reduction of solar magnetic field and solar activity like during Maunder minimum leading to noticeable reduction of terrestrial temperature as shown in Fig. 5. During this period, very few sunspots appeared on the surface of the Sun, and the overall brightness of the Sun was slightly decreased. The reconstruction of the cycle-averaged solar total irradiance back to 1610 (Figure 5, left plot) suggests a decrease of the solar irradiance during Maunder minimum by a value of about 3 $W/m^2$ (Fig. 5, left plot) (Lean et al., 1995), or about 0.22% of the total solar irradiance in 1710. The temperatures across much of the Northern Hemisphere of the Earth plunged down by1C (Fig. 5, right plot) when the Sun entered a quiet phase now called the Maunder Minimum (Easterbrook, 2016). This seemingly small decrease of an average temperature in Northern hemisphere led to frozen rivers, cold long winters and cold summers (Shindell et al, 2001). The similar pattern is expected in the modern GSM (2020-2053).

**Conclusions**

The recent progress with understanding a role of the solar background magnetic field in defining solar and with quantifying the observed magnitudes of magnetic field at different times activity enable reliable long-term prediction of solar activity on a millennium timescale. This approach revealed a presence of not only 11 year solar cycles but also of grand solar cycles with duration of 330-380 years. These grand cycles are always separated by grand solar minima of Maunder minimum type, with the modern GSM started in 2020 and to last until 2053.

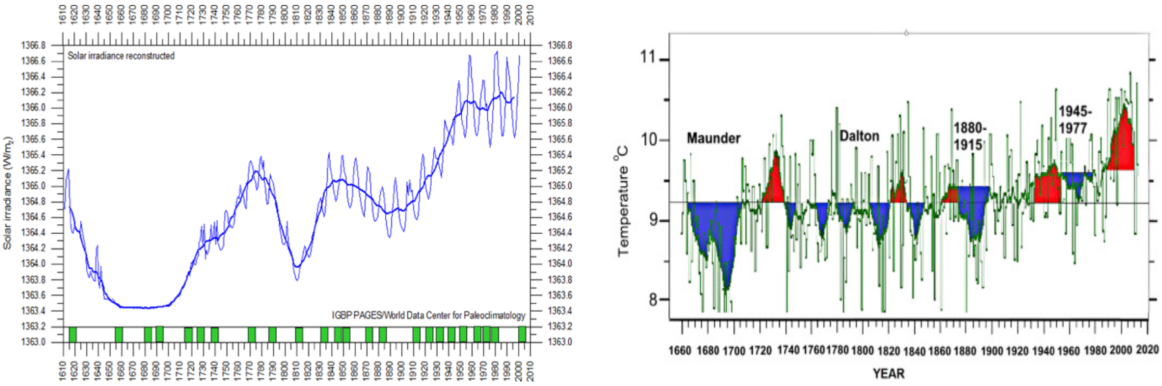


Figure 5. <u>Top plot:</u> restored total solar irradiance from 1600 until 2014 by Lean et al., 1995. <u>Bottom plot:</u> Central England temperatures (CET) recorded continuously since 1658. Blue areas are reoccurring cool periods; red areas are warm periods. All times of solar minima were coincident with cool periods in central England. Adopted from Easterbrook, 2016 with the Elsevier publisher permissions.

During these grand solar minima there is expected significant reduction of solar magnetic field and solar irradiance, which impose the reduction of terrestrial temperatures derived for these periods from the analysis of terrestrial biomass during the past 12 thousand or more years. The most recent grand solar minimum occurred during Maunder Minimum (1645-1710), which led to reduction of solar irradiance by 0.22% from the modern one and a decrease of the average terrestrial temperature by 1.0C.

The reduction of a terrestrial temperature during the next 30 years can have important implications for different parts of the planet on growing vegetation, agriculture, food supplies and heating needs in both Northern and Southern hemispheres. This global cooling during the upcoming grand solar minimum 1 (2020-2053) can offset for three decades any signs of global warming and *would require inter-government efforts to tackle problems with heat and food supplies for the whole population of the Earth*.

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