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FRONT MATTER: EDITORIAL

Modern Grand Solar Minimum will lead to terrestrial cooling

In this editorial I will demonstrate with newly discovered solar activity proxy-magnetic field that the Sun has entered into the modern Grand Solar Minimum (2020–2053) that will lead to a significant reduction of solar magnetic field and activity like during Maunder minimum leading to noticeable reduction of terrestrial temperature.

Sun is the main source of energy for all planets of the solar system. This energy is delivered to Earth in a form of solar radiation in different wavelengths, called total solar irradiance. Variations of solar irradiance lead to heating of upper planetary atmosphere and complex processes of solar energy transport toward a planetary surface.

The signs of solar activity are seen in cyclic 11-year variations of a number of sunspots on the solar surface using averaged monthly sunspot numbers as a proxy of solar activity for the past 150 years. Solar cycles were described by the action of solar dynamo mechanism in the solar interior generating magnetic ropes at the bottom of solar convective zone.

These magnetic ropes travel through the solar interior appearing on the solar surface, or photosphere, as sunspots indicating the footpoints where these magnetic ropes are embedded into the photosphere.

Magnetic field of sunspots forms toroidal field while solar background magnetic field forms poloidal field. Solar dynamo cyclically converts poloidal field into toroidal one reaching its maximum at a solar cycle maximum and then the toroidal field back to the poloidal one toward a solar minimum. It is evident that for the same leading polarity of the magnetic field in sunspots in the same hemisphere the solar cycle length should be extended to 22 years.

Despite understanding the general picture of a solar cycle, it was rather difficult to match the observed sunspot numbers with the modeled ones unless the cycle is well progressed. This difficulty is a clear indication of some missing points in the definition of solar activity by sunspot numbers that turned our attention to the research of solar (poloidal) background magnetic field (SBMF) [1].

By applying Principal Component Analysis (PCA) to the low-resolution full disk magnetograms captured in cycles 21–23 by the Wilcox Solar Observatory, we discovered not one but two principal components of this solar background magnetic field (see Figure 1, top plot) associated with two magnetic waves marked by red and blue lines. The authors derived mathematical formulae for these two waves fitting principal components from the data of cycles 21–23 with the series of periodic functions and used these formulae to predict these waves for cycles 24–26. These two waves are found generated in different layers of the solar interior gaining close but not equal frequencies [1]. The summary curve of these two magnetic waves (Figure 1, bottom plot) reveals the interference of these waves forming maxima and minima of solar cycles.

The summary curve of two magnetic waves explains many features of 11-year cycles, like double maxima in some cycles, or asymmetry of the solar activity in the opposite hemispheres during different cycles. Zharkova et al. [1] linked the modulus summary curve to the averaged sunspot numbers for cycles 21–23 as shown in Figure 2 (top plot) and extended this curve to cycles 24–26 as shown in Figure 2 (bottom plot). It appears that the amplitude of the summary solar magnetic field shown in the summary curve is reducing toward cycles 24–25 becoming nearly zero in cycle 26.

Zharkova et al. [1] suggested to use the summary curve as a new proxy of solar activity, which utilizes not only amplitude of a solar cycle but also its leading magnetic polarity of solar magnetic field.

Figure 3 presents the summary curve calculated with the derived mathematical formulae forwards for 1200 years and backwards 800 years. This curve reveals appearance of Grand Solar Cycles of 350–400 years caused by the interference of two magnetic waves. These grand cycles are separated by

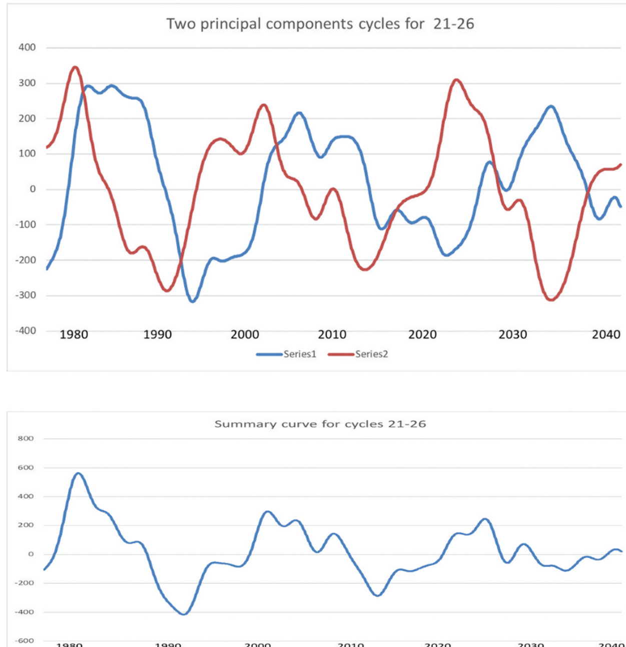

Figure 1. Top plot: two principal components (PCs) of solar background magnetic field (blue and green curves, arbitrary numbers) obtained for cycles 21–23 (historic data) and predicted for cycles 24–26 using the mathematical formulae derived from the historical data (from the data by Zharkova et al. [1]). The bottom plot: The summary curve derived from the two PCs above for the "historical" data (cycles 21–23) and predicted for solar cycle 24 (2008–2019), cycle 25 (2020–2031), cycle 26 (2031–2042) (from the data by Zharkova et al. [1]).

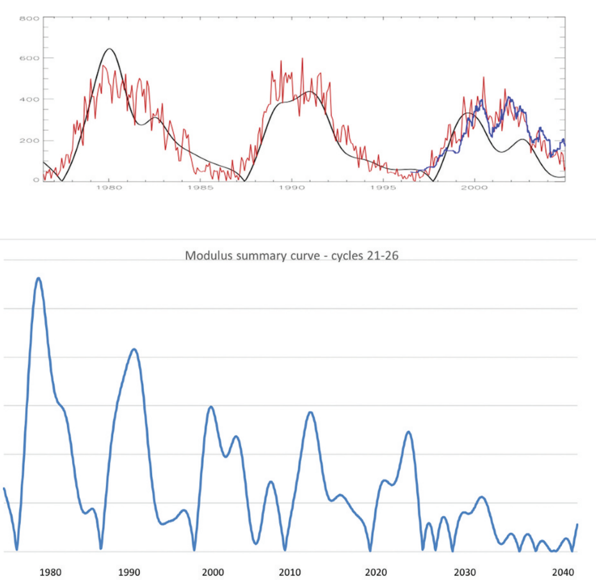

Figure 2. Top plot: The modulus summary curve (black curve) obtained from the summary curve (Figure 1, bottom plot) versus the averaged sunspot numbers (red curve) for the historical data (cycles 21–23). Bottom plot: The modulus summary curve associated with the sunspot numbers derived for cycles 21–23 (and calculated for cycles 24–26 (built from the data obtained by Zharkova et al. [1])).

the grand solar minima, or the periods of very low solar activity [1]. The previous grand solar minimum was Maunder minimum (1645–1710), and the other one before named Wolf minimum (1270–1350). As seen in Figure 3 from prediction by Zharkova et al. [1], 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 24th century (2370–2415).

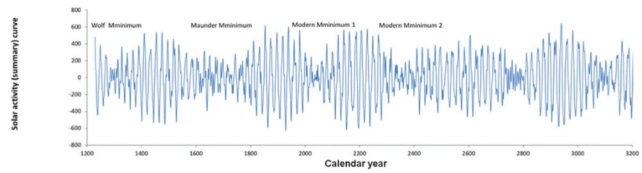

Figure 3. Solar activity (summary) curve restored for 1200–3300 AD (built from the data obtained by Zharkova et al. [1]).

The observational properties of the two magnetic waves and their summary curve were closely fit by double dynamo waves generated by dipole magnetic sources in two layers of the solar interior: inner and outer layers [1], while other three pairs of magnetic waves can be produced by quadruple, sextuple, and octuple magnetic sources altogether with dipole source defining the visible appearance of solar activity on the surface.

Currently, the Sun has completed solar cycle 24 – the weakest cycle of the past 100+ years – and in 2020, has started cycle 25. During the periods of low solar activity, such as the modern grand solar minimum, the Sun will often be devoid of sunspots. This is what is observed now at the start of this minimum, because in 2020 the Sun has seen, in total, 115 spotless days (or 78%), meaning 2020 is on track to surpass the space-age record of 281 spotless days (or 77%) observed in 2019. However, the cycle 25 start is still slow in firing active regions and flares, so with every extra day/week/month that passes, the null in solar activity is extended marking a start of grand solar minimum. What are the consequences for Earth of this decrease of solar activity?

Total solar irradiance (TSI) reduction during Maunder Minimum

Let us explore what has happened with the solar irradiance during the previous grand solar minimum – Maunder Minimum. 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 4, top plot) suggests a decrease of the solar irradiance during Maunder minimum by a value of about 3 W/m^2 [2], or about 0.22% of the total solar irradiance in 1710, after the Maunder minimum was over.

Temperature decrease during Maunder minimum

From 1645 to 1710, the temperatures across much of the Northern Hemisphere of the Earth plunged when the Sun entered a quiet phase now called the Maunder Minimum. This likely occurred because the total solar irradiance was reduced by 0.22%, shown in Figure 4 (top plot) [2], that led to a decrease of the average terrestrial temperature measured mainly in the Northern hemisphere in Europe by 1.0–1.5°C as shown in Figure 4 (bottom plot) [3]. This seemingly small decrease of the average temperature in the Northern hemisphere led to frozen rivers, cold long winters, and cold summers.

The surface temperature of the Earth was reduced all over the Globe (see Figure 1 in [4]), especially, in the countries of Northern hemisphere. Europe and North America went into a deep freeze: alpine glaciers extended over valley farmland; sea ice crept south from the Arctic; Dunab and Thames rivers froze regularly during these years as well as the famous canals in the Netherlands.

Shindell et al. [4] have shown that the drop in the temperature was related to dropped abundances of ozone created by solar ultra-violate light in the stratosphere, the layer of the atmosphere located between 10 and 50 kilometers from the Earth's surface. Since during the Maunder Minimum the Sun emitted less radiation, in total, including strong ultraviolet emission, less ozone was formed affecting planetary atmosphere waves, the giant wiggles in the jet stream.

Shindell et al. [4] in p. 2150 suggest that "a change to the planetary waves during the Maunder Minimum kicked the North Atlantic Oscillation (NAO) – the balance between a permanent low-pressure system near

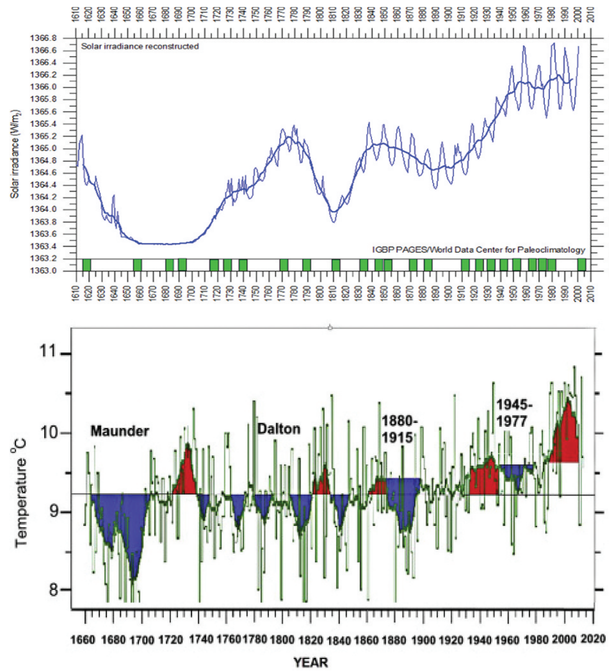

Figure 4. Top plot: restored total solar irradiance from 1600 until 2014 by Lean et al. [2]. Modified by Easterbrook [3], from Lean, Beer, Bradley [2]. Bottom plot: Central England temperatures (CET) recorded continuously since 1658. Blue areas are reoccurring cool periods; red areas are warm periods. All times of solar minima were coincident with cool periods in central England. Adopted from Easterbrook [3], with the Elsevier publisher permissions.

Greenland and a permanent high-pressure system to its south – into a negative phase, that led to Europe to remain unusually cold during the MM."

Role of magnetic field in terrestrial cooling in Grand Solar Minima

However, not only solar radiation was changed during Maunder minimum. There is another contributor to the reduction of terrestrial temperature during Maunder minimum – this is the solar background magnetic field, whose role has been overlooked so far. After the discovery [1] of a significant reduction of magnetic field in the upcoming modern grand solar minimum and during Maunder minimum, the solar magnetic field was recognized to control the level of cosmic rays reaching planetary atmospheres of the solar system, including the Earth. A significant reduction of the solar magnetic field during grand solar minima will undoubtedly lead to the increase of intensity of galactic and extra-galactic cosmic rays, which, in turn, lead to a formation of high clouds in the terrestrial atmospheres and assist to atmospheric cooling as shown by Svensmark et al. [5].

In the previous solar minimum between cycles 23 and 24, the cosmic ray intensity increased by 19%. Currently, solar magnetic field predicted in Figure 1 by Zharkova et al. [1] is radically dropping in the sun that, in turn, leads to a sharp decline in the sun's interplanetary magnetic field down to only 4 nanoTesla (nT) from typical values of 6 to 8 nT. This decrease of interplanetary magnetic field naturally leads to a significant increase of the intensity of cosmic rays passing to the planet's atmospheres as reported by the recent space missions [6]. Hence, this process of solar magnetic field reduction is progressing as predicted by Zharkova et al. [1], and its contribution will be absorbed by the planetary atmospheres including Earth. This can decrease the terrestrial temperature during the modern grand solar minimum that has already started in 2020.

Expected reduction of terrestrial temperature in modern Grand Solar Minima

This summary curve also indicated the upcoming modern grand solar minimum 1 in cycles 25–27 (2020–2053) and modern grand solar minimum 2 (2370–2415). This will bring to the modern times the unique low activity conditions of the Sun, which occurred during Maunder minimum. It is expected that during the modern grand solar minimum, the solar activity will be reduced significantly as this happened during Maunder minimum (Figure 4, bottom plot). Similarly to Maunder Minimum, as discussed above, the reduction of solar magnetic field will cause a decrease of solar irradiance by about 0.22% for a duration of three solar cycles (25–27) for the first modern grand minimum (2020–2053) and four solar cycles from the second modern grand minimum (2370–2415).

This, in turn, can lead to a drop of the terrestrial temperature by up to 1.0°C from the current temperature during the next three cycles (25–27) of grand minimum 1. The largest temperature drops will be approaching during the local minima between cycles 25 – 26 and cycles 26–27 when the lowest solar activity level is achieved using the estimations in Figure 2 (bottom plot) and Figure 3. Therefore, the average temperature in the Northern hemisphere can be reduced by up to 1.0°C from the current temperature, which was increased by 1.4°C since Maunder minimum. This will result in the average temperature to become lower than the current one to be only 0.4°C higher than the temperature measured in 1710. Then, after the modern grand solar minimum 1 is over, the solar activity in cycle 28 will be restored to normal in the rather short but powerful grand solar cycle lasting between 2053 and 2370, as shown in Figure 3, before it approaches the next grand solar minimum 2 in 2370.

Conclusions

In this editorial, I have demonstrated that the recent progress with understanding a role of the solar background magnetic field in defining solar activity and with quantifying the observed magnitudes of magnetic field at different times allowed us to 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 350–400 years. We demonstrated that these grand cycles are formed by the interferences of two magnetic waves with close but not equal frequencies produced by the double solar dynamo action at different depths of the solar interior. These grand cycles are always separated by grand solar minima of Maunder minimum type, which regularly occurred in the past forming well-known Maunder, Wolf, Oort, Homeric, and other grand minima.

During these grand solar minima, there is a 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 12,000 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 1.0–1.5°C.

This discovery of double dynamo action in the Sun brought us a timely warning about the upcoming grand solar minimum 1, when solar magnetic field and its magnetic activity will be reduced by 70%. This period has started in the Sun in 2020 and will last until 2053. During this modern grand minimum, one would expect to see a reduction of the average terrestrial temperature by up to 1.0°C, especially, during the periods of solar minima between the cycles 25–26 and 26–27, e.g. in the decade 2031–2043.

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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