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Forecasting the Peak Amplitude of the 24th and 25th Sunspot Cycles and Accompanying Geomagnetic Activity

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Abstract Forecasting solar and geomagnetic levels of activity is essential to help plan missions and to design satellites that will survive for their useful lifetimes. Therefore, amplitudes of the upcoming solar cycles and the geomagnetic activity were forecasted using the neuro-fuzzy approach. Results of this work allow us to draw the following conclusions: Two moderate cycles are estimated to approach their maximum sunspot numbers, 110 and 116 in 2011 and 2021, respectively. However, the predicted geomagnetic activity shown to be in phase with the peak of the 24th sunspot cycle will reach its minimum three years earlier, then it will rise sharply to reach the 25th maximum a year earlier (*i.e.*, 2020). Our analysis of the three-century long sunspot number data-set suggests that the quasi-periodic variation of the long-term evolution of solar activity could explain the irregularity of the short-term cycles seen during the past decades.

1. Introduction

Because the nature of the sunspot cycle is not yet completely understood, a challenge for solar physicists is to forecast the strength of the forthcoming cycles. Some attempts have been made to shed light on the physical processes responsible for sunspot activity and to provide a better understanding of some of the rules, such as the Gnevyshev – Ohl and Waldmeier relations, which suffered a random phase jump during the past three cycles. This implies a stochastic or chaotic component, which limits the predictability of the solar cycle. Usoskin and Mursula (2003) reviewed recent advances to explain the nature of randomness in sunspot activity and some of these findings provide a new insight into the long-term change known as the secular Gleissberg cycle (Gleissberg, 1944). One of these models (Rozelot, 1994) suggests that fluctuations of the observed sunspot numbers were supposed to be due to noise that was added to the regular part and plays no role in solar cycle evaluation. This approach does not adequately describe the long-term evolution. Ruzmaikin (1997, 1998) suggested that a combination of the regular dynamo and random fields could exceed the buoyancy

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threshold. Corbard *et al.* (2002) improved this model and qualitatively reproduced some features of the sunspot cycle. Usoskin, Mursula, and Kovaltsov (2001) built a similar model of sunspot activity, including a superposition of a regular 11-year oscillating dynamo-related field (weak magnetic field) and a randomly fluctuating component. This model was found to reproduce fairly well most of the fundamental features of sunspot cyclicity, both for normal times and great minima. However, the predictability of sunspot activity is limited according to this theory. Among various combinations of methodologies in computing, the one that has highest visibility at this juncture is that of fuzzy logic and neuro-computing, leading to the so-called neuro-fuzzy model. By the late 1990s, the neuro-fuzzy-based approach was widely accepted as a promising tool, particularly in the field of solar-terrestrial time series. It provides more precise results compared with other methods (*e.g.*, MacPherson, 1994; Macpherson, Conway, and Brown, 1995; Fessant, Pierret, and Lantos, 1996; Conway, 1998; Kugblenu, Taguchi, and Okuzawa, 1999).

2. Data and Methods of Analysis

Annual records of Wolf (W) and sunspot group numbers archived from 1700 at NOAA (ftp://ftp.ngdc.noaa.gov/STP/Solar_Data) were analyzed. We also used the available records of the geomagnetic *aa* index (ftp://ftp.ngdc.noaa.gov/STP/Geomagnetic) from 1874. For prediction, we preferred to use the Wolf number data as a measure of the solar activity for direct comparison with the results of other published methods. To examine the long-term cyclic variations of solar activity, we applied a spectral analysis (single fast Fourier transform), comprising a complex time series with cyclical components of a few underlying sinusoidal functions of particular wavelengths. This technique focuses on the exploration of cyclical patterns of data. It is noteworthy that the length of time covered by the data-set analysed by this method must be three times that of the longest period in order to obtain meaningful results.

In the field of artificial intelligence, neuro-fuzzy refers to hybrids of artificial neural networks and fuzzy logic. Neuro-fuzzy hybridization results in a hybrid intelligent system that synergizes these two techniques by combining the human-like reasoning style of fuzzy systems with the learning and connectionist structure of neural networks. Neuro-fuzzy hybridization is widely termed as a fuzzy neural network or a neuro-fuzzy system in the literature, the latter of which is the more popular term and is used henceforth. A neuro-fuzzy system incorporates the human-like reasoning style of fuzzy systems through the use of fuzzy sets and a linguistic model consisting of a set of IF – THEN fuzzy rules. The main strength of neuro-fuzzy systems is that they are universal approximators with the ability to solicit interpretable IF – THEN rules. After a number of different configurations are tried, the neuro-fuzzy structure is optimized based on the linear adapted genetic algorithm with controlling population size (LAGA-POP). The dimension of the time series attractor is obtained based on the smallest regularity criterion and the FLNN model. For a more detailed description of the neuro-fuzzy model, the reader referred to Attia, Hamid, and Maha (2005).

3. Results and Discussion

3.1. Results of the Prediction

Our model results agreed with our preliminary expectations; the next cycles cover the minimum stage of the century-long cycle. Therefore they should have a lower intensity than

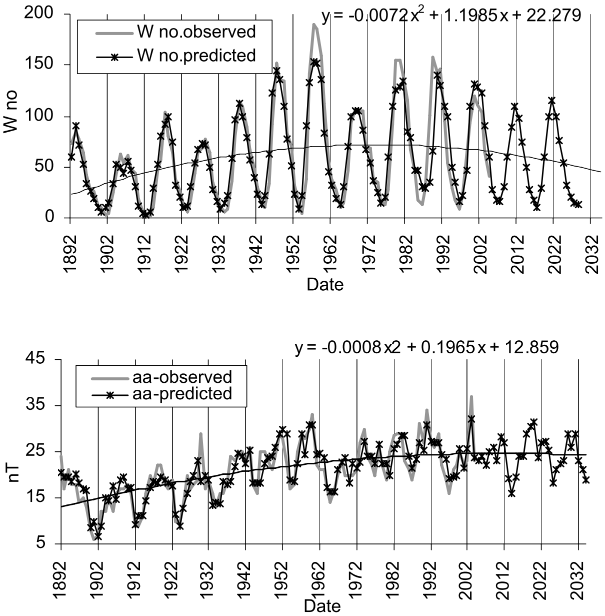

Figure 1 Top: Comparison between the observed Wolf numbers (gray line) and calculated ones (black line) during the period 1892 – 2028. Bottom: Values of the *aa* index during the period 1892 – 2034. The equation shown in both charts indicates the fitted trend.

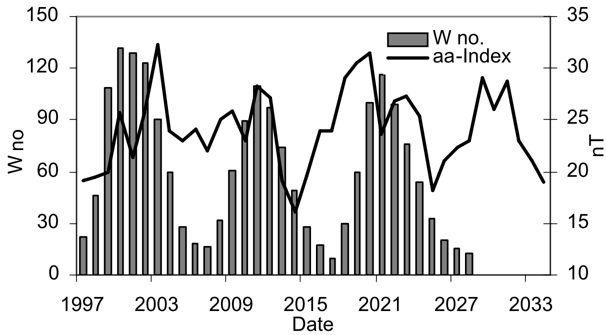

Figure 2 The calculated sunspot numbers (columns) and *aa* index (line) for cycles 23, 24, and 25.

the past three cycles or at least comparable to the 23rd one. As shown in the upper diagram of Figure 1, the model successfully met the last extremes of the solar cycles, but the sharp peaks (*e.g.*, 19th, 21st, and 22nd cycles) displayed differences between the calculated and observed values ranging from ±7% of the annual mean or weak cycles to 18% for intense ones. According to this model, two moderate cycles are foreseen during the periods 2007 – 2017 and 2017 – 2028. The 24th and 25th maxima are estimated to arise in 2011 and 2021 with sunspot numbers 110 and 116, respectively. Tritakis, Mavromichalaki, and Giouvanellis (2006) calculated the duration of the 24th and 25th solar cycles depending on interdependence between successive 11-year and 22-year cycles.

It is well known that the geomagnetic and sunspot indices, because of their different nature, do not exhibit similar variations and often manifest out-of-phase behavior (Stamper *et al.*, 1999). For the predicted duration the geomagnetic field corresponding to the period of sunspot minimum (2004 – 2008) shows a moderate level. As seen in Figure 1 the *aa* index deep minimum will come in 2014.

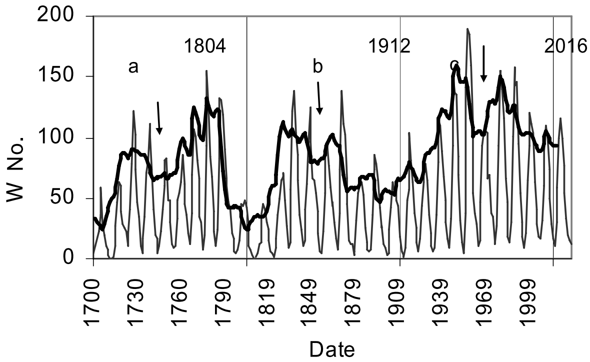

Figure 3 The smoothed curve (10-year moving average) of the 11-year cycles presents the long-term variation of sunspot numbers from 1700. The small arrows point to the drop of Wolf numbers at the maximum phase of the century-long cycle (at about the 50th years).

The phase shift between the sunspot numbers and the *aa* index is clear in Figure 2; the maximum of the geomagnetic activity of the 24th cycle synchronizes with that of sunspots and seems lower than the annual mean observed in 2000 and 2001 whereas it shows more evolution in 2020 (25th peak), as the solar activity lags the *aa* index by a year, and afterward reached its deep minimum three years before the sunspot cycle. Inspecting the trend lines through the solar and geomagnetic courses in Figure 1 we can see that the century-long cycle reaches its end through the course of the solar activity whereas it remains in a high phase in geomagnetic activity. This finding tells us that the activity at the end of the 20th century has a higher average level than that at the beginning of this century. This result agrees with that of Mursula, Martini, and Karinen (2004); their study, based on the *aa* index, revealed that open solar magnetic field has increased during the past 100 years.

Our model results agree with some contributions and contradict others. For instance, Hamid and Galal (2006) proposed a method depending on the number of spotless days during the preceding minimum; they predicted the 24th solar maximum to be 90.7 ± 9.2 with a rise time of 4.6 ± 1.2 years. Svalgaard, Edward, and Kamide (2005) proposed that the coming peak will be the smallest in the past 100 years, with a smoothed monthly sunspot number of 75 ± 8(reaching its peak in 2011). Their method is based on a dynamo model in which large-scale polar fields at the declining phase of the 11-year solar cycle are converted to toroidal (sunspot) field of the subsequent cycle. However, several studies of the solar – climate relationship predicted a decrease in solar activity during the next two cycles inferred from some climatic parameters (*e.g.*, Yousef, 2003, and references therein). In contrast, solar scientists at the National Center for Atmospheric Research expect the next sunspot cycle could be 30% to 50% stronger than the last one (Dikpati, Giuliana, and Peter, 2006), and they expect the cycle to begin about 6 – 12 months later than a cycle would normally start and peak in 2012. NASA solar physicists (Hathaway and Wilson, 2006) agree, but their timing prediction differs. They predict 160 ± 25 sunspot numbers for the 24th peak, but they expect cycle 25 to be extraordinarily weak. Chopra and Dabas (2006) predict a maximum amplitude of 140 for the forthcoming solar cycle.

3.2. Long-Term Variations of Solar Activity

The smoothed curve (10-year running average) in Figure 3 identifies three century-long cycles of sunspot activity (with epochs labeled a, b, and c) starting from 1700 going forward. It is known that the long-term cycle could range from 92 years long, such as that covering the 19th century (part b), up to 116 years, as expected for the latest cycle. A drop in sunspot numbers appears significant about 50 years after the start of the century-long cycle

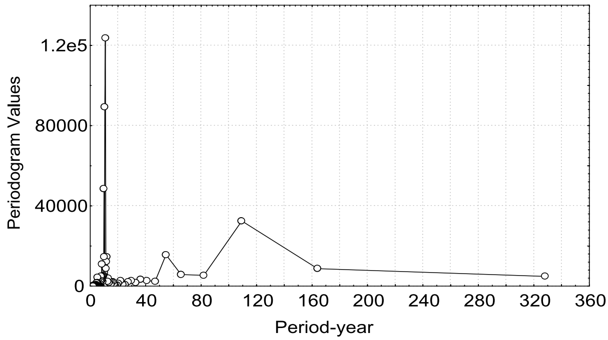

Figure 4 Spectral analysis of Wolf numbers. Periods of ∼ 53 years and 109 years are clear in addition to the main period of 11 years.

(placed on its maximum phase). This performance could explain the weakness in solar and geomagnetic activity of cycle 20. As a result of this modulation, the maximum phase of the century-long cycle has two peaks. These two periods could be comparable, in duration and amplitude, as seen in the past cycles (nos. 17, 18, 19 and 20, 21, 22), or dissimilar as shown in the early centuries.

To confirm the periodicity of this variation, a time series analysis of sunspot numbers (for 328 annual means) was applied. The periodogram shown in Figure 4 signifies a weak peak at 53 years, in addition to the significant peaks at 11 and 109 years. Unfortunately, we could not examine this period in the *aa* index by the same method because of the short interval of data. This result will help us understand the periodic and quasi-periodic variations of the long-term trend and could introduce an explanation for the similarity between odd and even cycles, such as the weak cycles 17, 20, and 23 and the enhanced cycles 18, 19, 21, and 22 (according to their position on the century-long cycle), which seem a break from the Gnevyshev – Ohl rule.

Hydrodynamical studies are needed to clarify the mechanism of this modulation in the long term. The analysis by Andryeyeva and Stepanian (2006) revealed the existence of two groups of large-scale magnetic fields evolving differently during the cycles; their results support the idea of two different dynamo mechanisms operating in the Sun.

4. Conclusion

The presented prediction for the next two cycles estimates two moderate cycles of maximum annual mean sunspot numbers of about 110 and 116. This estimation is considered reasonable because of their position in the century-long cycle. Cycle 23 sunspot activity is expected to reach its lowest value in 2007; however, the geomagnetic field still displays a moderate level during this period, which may indicate a continuation of the open magnetic field beginning two cycles before. This also gives the impression that the geomagnetic activity during the next great minimum will be higher than the former one. The estimated *aa* index will reach its lowest value in 2014, which may represent the actual end of the current long-term cycle. The maximum of solar and geomagnetic activities will be in phase during cycle 24 but the latter will come to its 25th peak a year earlier than sunspots. The *aa* index will reach its minimum three years earlier than that of sunspots in cycles 24 and 25.

A quasi-periodic variation of 50 years, on average, was verified by using spectral analysis. This means that the long-term solar cycle experiences a short-lived quietness during its maximum phase just like that which sporadically occurs in the 11-year cycle. Our results hint that the long-term solar cycle and the quasi-periodic variations superimposed on it may explain the shown irregularity of the short-term solar cycles and accordingly the geomagnetic disturbances.

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