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Prediction of sunspot number amplitude and solar cycle length for cycles 24 and 25

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ABSTRACT

The prediction of solar activity strength for solar cycles 24 and 25 is made on the basis of extrapolation of sunspot number spectral components. Monthly sunspot number data during the 1850–2007 interval (solar cycles 9–23) are decomposed into several levels and searched for periodicities by iterative regression in each level. For solar cycle 24, the peak is predicted in November 2013 with a sunspot number of 113.3. The cycle is expected to be weak, with a length of 133 mo (months) or 11.1 yr. The sunspot number maximum in cycle 25 is predicted to occur in April 2023 with a sunspot number 132.1 and a solar cycle length of 118 mo or 9.8 yr. Thus, solar cycle 24 is predicted to have an intensity 23% lower than cycle 23, and cycle 25 will be 5% lower than cycle 23.

1. Introduction

The prediction of solar activity and especially of the sunspot cycle amplitude and length is one of the most active fields in space weather research. Nowadays, the great challenge for space science is to predict the characteristics of the next solar cycle, e.g. predicting the solar activity during the solar cycle using sunspot series that are already available (Eddy, 1976; Hoyt and Schatten, 1997; Souza Echer et al., 2009, Hathaway, 2010).

Over a solar cycle, Sun's activity has a dramatic effect on Earth's surface and atmosphere such as the variation in Earth's climate, which may be caused by varying UV and total radiation from the Sun (Eddy, 1976; Hoyt and Schatten, 1997, Haigh, 2007; Souza Echer et al., 2009).

Furthermore, coronal mass ejections and interplanetary shock waves produced on the Sun are responsible for geomagnetic activity, storms and auroras (Webb and Howard, 1994; Echer et al., 2004). There is also a high probability for the occurrence of large solar flare associated solar energetic particles, which can cause phenomena such as communications disturbances, failures in electronic solid state components, etc. (Echer et al., 2005; Siscoe, 2000). The strength of these events depends on the intensity of solar cycle activity, which is extremely variable.

These facts justify the scientific and practical importance of predicting the solar cycle strength. This can be done using a great number of techniques, as shown by Kane (2007). Creating a realistic model of the solar dynamo would be the best approach for this; however such models do not exist yet. For this reason mathematical analysis of cycle trends, such as spectral analysis, is used to predict solar activity (Rigozo et al., 2001; Echer et al., 2004; Nordemann et al., 2008). Other innovative techniques are based on statistical dependences between solar and geophysical parameters (Kane, 2007).

In this paper, a spectral analysis as well as regression interactive method of monthly and annual averages of sunspot numbers is used to predict the solar activity (minimum and maximum) and solar cycle length for cycles 24 and 25. This method using sunspot number periodicities to study solar activity was used successfully by Rigozo et al. (2001). A sunspot number reconstruction through its periodicities was performed for the 1700–1999 time intervals and extended to the past 1000 years. These authors gave a good representation of solar minimum activity epochs (Oort, Wolve, Spörer, Maunder and Dalton solar minima) and solar maximum activity epochs (Medieval and Modern solar maxima). Echer et al. (2004), also studying solar activity periodicities for the 1850–2000 time intervals, reconstructed sunspot number and predicted an annual average sunspot number of 125.0 ± 13.2 for cycle 23, whereas the later on observed value was 119.6. Another method to study the predictability of solar activity through its periodicities was performed by Nordemann et al. (2008) who predicted a weaker next solar cycle to occur in 2010 with amplitude of 100 sunspots. Kane (1999), Rigozo et al. (2001), Echer et al. (2004) and Nordemann et al. (2008) have shown that the use of periodicities

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found in sunspot time series is an excellent way to study past sunspot numbers and to predict their future.

2. Data and analysis

2.1. Spectral analysis

The monthly average of sunspot number for 1850–2007 (shown in Fig. 1) obtained from the Sunspot Index Data Center in Brussels, Belgium is used in this analysis. Since the Wolf sunspot number is more reliable after 1850 (Hoyt and Schatten, 1998a, b), only sunspot data after this date is used in this work. It is well known from classical spectral analysis (ARIST, Análise por Regressão Iterativa de Series Temporais) that a quasi-stationary and quasi-periodical time series can be represented by a sum of sine functions of N periods (more details in Wolberg, 1967; Rigozo and Nordemann, 1998; Rigozo et al. 2005), namely,

$$f(t)=\sum_{i=1}^{N} r_i \sin\left(2\pi\frac{1}{T_i}+\phi_i\right) \tag{1}$$

Where r is the amplitude, T the period, ϕ the phase of function, i the number of sine functions and N the total number of sine functions used for the prediction.

2.2. Decomposition of time series

In order to improve the estimation of periods of the spectrum, since the long periods hinder the detection of low periods, we employ a filtering procedure using wavelet analysis (Weng and Lau, 1994; Kumar and Foufoula-Georgiou, 1997). The sunspot number data was decomposed into ten spectral bands by using an orthonormal Meyer wavelet (more details in Kumar and Foufoula-Georgiou, 1997, Percival and Walden, 2000). The frequency bands are approximately: L_1 (2–4 mo), L_2 (4–8 mo), L_3 (8–16 mo), L_4 (16–32 mo), L_5 (32–64 mo), L_6 (64–128 mo), L_7 (128–256 mo), L_8 (256–512 mo), L_9 (512–1024 mo) and L_{10} (> 1024 mo). L_{10} is the scaling level, corresponding to long-term periods (Fig. 2).

The wavelet decomposition process can be iterated, with successive approximations being decomposed in turn, so that a signal is broken down into many lower resolution components. This is called the 'wavelet decomposition tree'. Since the analysis process is iterative, in theory it can be continued indefinitely. In reality, the decomposition is performed only until individual details limited by sample or pixel size. In practice, one selects a suitable number of levels based on the nature of the signal, or on a suitable criterion such as wavelet entropy (Percival and Walden, 2000).

In this work ten levels were chosen to decompose the Wolf sunspot number data: levels 1–10 are bands of frequencies and are proportional to the differences in relation to the average data. The 10th level is the long-term trend. The decomposition bands of the sunspot number (R_z) data obtained with wavelet analysis are shown in Fig. 2. In the nine lowest period bands (from upper to lower panel in Fig. 2), an iterative regression analysis (ARIST) method was applied and gave estimates of periodicities, amplitudes and phase (Rigozo et al., 2001; Rigozo et al., 2008). Several periodical signals were obtained for each band. The frequencies were selected at the 95% confidence level.

The 10th wavelet decomposition band (the lowest panel in Fig. 2) is not a full wave, but it indicates a long-term trend or period in the sunspot activity. In Fig. 3 the periods that are considered statistically significant for each decomposition level are shown. The reconstructed sunspot number was then obtained by applying the periods listed in Fig. 3 and Eq. (1).

3. Results

Fig. 3 shows the ARIST spectral amplitude as a function of frequency as determined by the ARIST method using levels L_2–L_{10}. The periods indicated are significant at 95% confidence level (amplitude $> 2\sigma$). The L_1 level corresponds to the high-frequency oscillations, from the Nyquist cutoff frequency (2 mo) to 4 mo. It is relatively difficult to find any pattern in this high-frequency, noisy band. Therefore this level is not used in the reconstruction. The reconstruction is done through the addition of all the

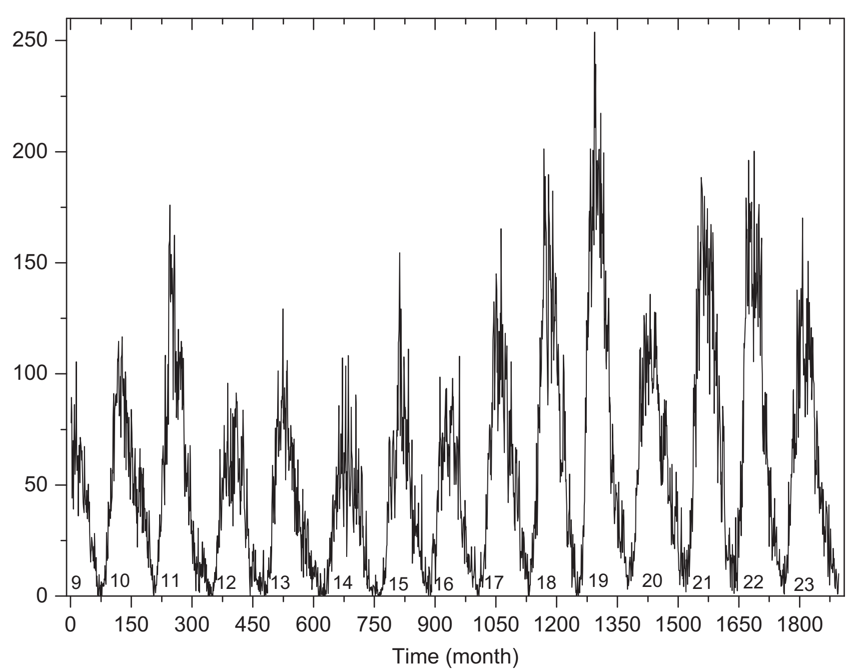

Fig. 1. Monthly sunspot number time series for 1850–2007.

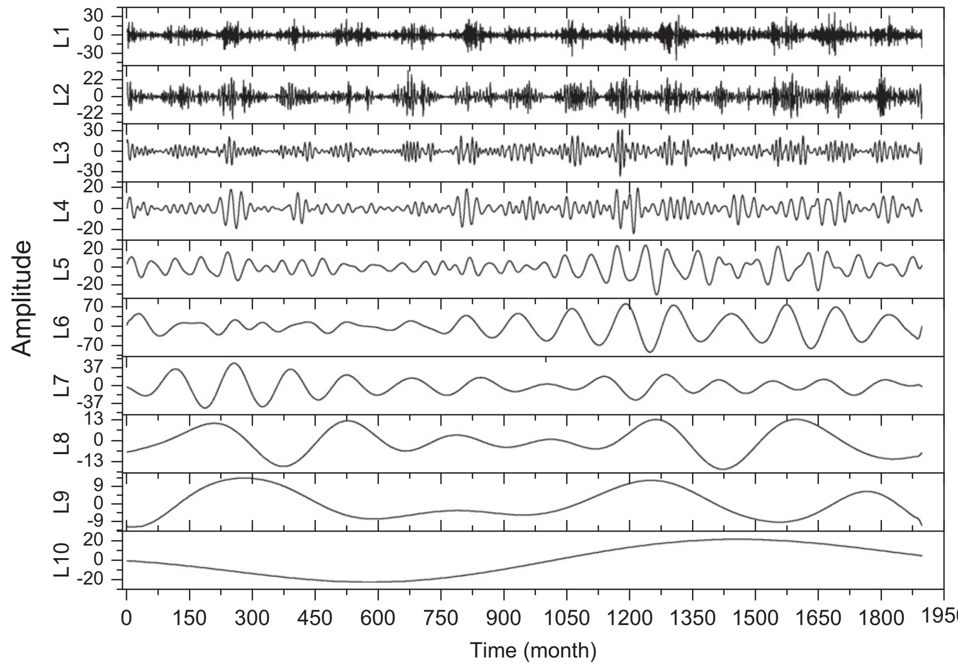

Fig. 2. Decomposition by multiple regression analysis (MRA) of the monthly sunspot number time series in 10 levels (axis x=time, months and axis y=amplitude).

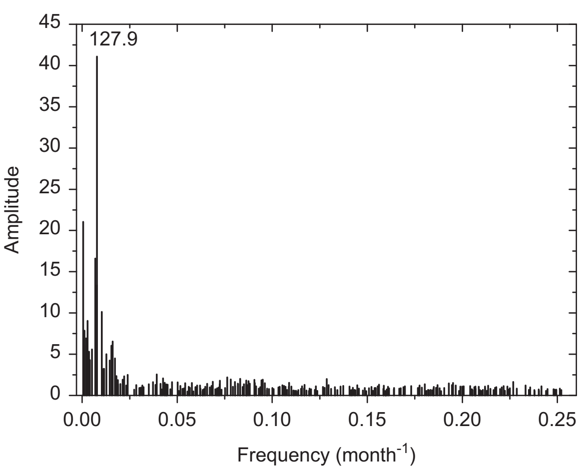

Fig. 3. Amplitude spectrum for sunspot number decomposition (127 mo is the 11 yr solar cycle).

periodicities found, applying Eq. (1) for all levels by the ARIST method (Rigozo et al., 2005), since it determines the amplitude, frequency and phase. A correlation analysis between the reconstructed and original data was performed, giving a high correlation coefficient of r=0.86, producing a common variance (r^2) of about 74%.

Fig. 4 shows the reconstructed series (dotted red line), by ARIST method considering all decomposition levels, and the original sunspot number time series (black line). The sunspot series was extrapolated until month 2148 to predict solar cycles 24 and 25 (Fig. 4A). Some negative R_z values were obtained by the sine wave calculation and were set to zero, because they do not have not a physical significance. The correspondence is reasonable, especially in terms of sunspot cycle maximum amplitudes. It may be seen in Fig. 4A that solar cycles 24 and 25 are predicted to be smaller than solar cycle 23. However, the solar cycle 25 is predicted to be more intense than solar cycle 24. The sunspot number maximum in cycle 24 is predicted to occur in November 2013 with a sunspot number of 113.3 and a solar cycle length of 133 mo. The sunspot number maximum in cycle 25 is predicted to occur in April 2023 with a sunspot number of 132.1 and it presents a solar cycle length of 118 mo.

4. Discussion

Maris and Oncica (2006) reported that the solar cycle maximum in cycle 24 will occur in December 2009 with a sunspot number of 145. Tsirulnik et al. (1997) reported that solar cycle 24 presents your maximum in 2014 with a sunspot number of 180. Echer et al. (2004) predicted that solar maximum 24 will happen in 2013 with a sunspot number of 117 ± 13.2. In this work we predicted that the solar cycle 24 maximum annual average will occur in 2013 with a sunspot number of 92.6 (Fig. 4B). Solar cycle 25 maximum annual average will occur in 2023 with a sunspot number value of 113.4 (Fig. 4B). Choudhuri et al. (2007) found that cycle 24 would be 35% lower than cycle 23. In this work it was found that solar cycle 24 would be 23% lower than solar cycle 23 and solar cycle 25 would be 5% lower than cycle 23. Table 1 shows various predictions found in the literature as well as the results of this study.

In this work, we performed a comparison between four predictions of cycle 24: (i) using two cycles 22 and 23; (ii) using three cycles (21–23); (iii) using four cycles (20–23) and (iv) the last prediction considered the sunspot number time series for 1850–2007 time interval (in other words, the solar activity of 100-yr long modulation trend of the sunspot number). These predictions are shown in Fig. 5. In the first three cases Fig. 5A–C shows that cycle 24 has a smaller peak (in terms of height) than cycle 23. If considering Figs. 5A–C, with only 2, 3 and 4 cycles for the prediction, cycle 24 should be about 8%, 16% and 17.5% smaller than cycle 23, respectively. This occurs because 100-yr modulation of solar activity was not considered. Fig. 5D presents the prediction taking into account the long trend of solar activity, showing that cycle 24 would be 23% lower than cycle 23. The above results show the importance of also using long trend data for solar cycle prediction.

Many authors cite the importance of considering the long trends of solar activity to assess more accurately the solar cycle of

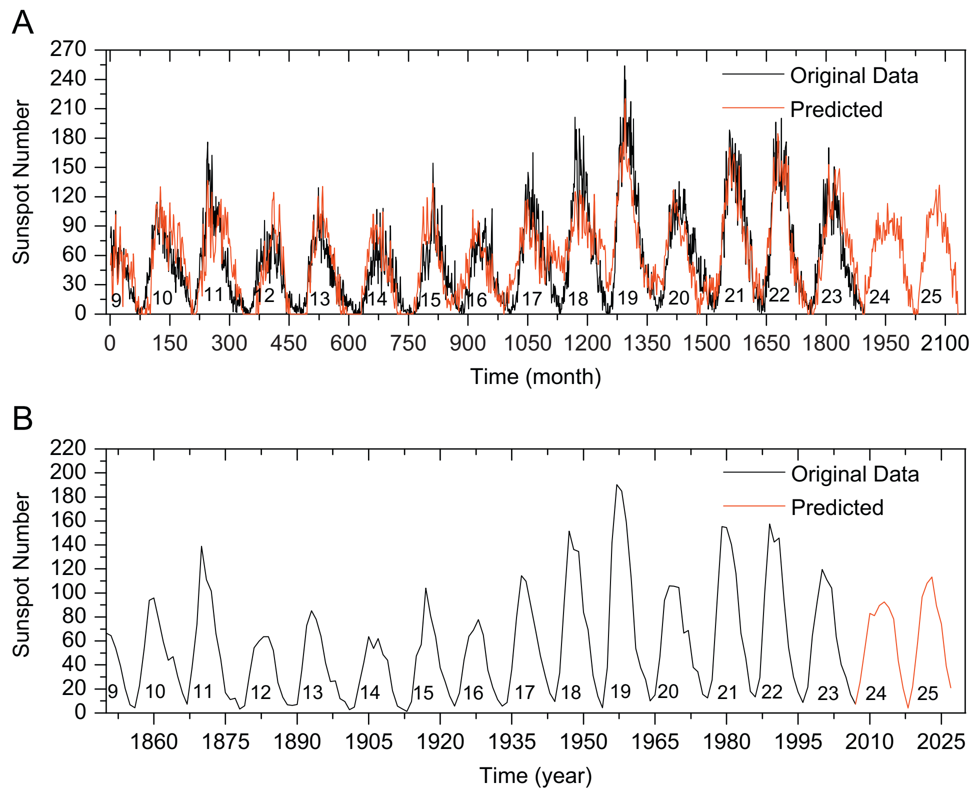

Fig. 4. (A) Monthly sunspot number time series (black line). Reconstructed and predicted data monthly sunspot number time series (red line). (B) Annual sunspot number time series (black line) and predicted annual sunspot number time series (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Results of solar cycle 24 peak predictions by several authors using different techniques.

Prediction	Max. #24	Prediction	Max. #24
Tsirulnik et al. (1997)	180	Hathaway and Wilson (2006)	160
Kane (1999)	140 ± 9	Hamid and Galal (2006)	91
Wang et al. (2002)	83.2–119.4	Maris and Oncica (2006)	145
Khramova et al. (2002)	123–124	Chopra and Dabas (2006)	140
Duhau (2003)	87.5 ± 23.5	Dikpati and Gilman (2006)	160–180
Echer et al. (2004)	115-117 $\pm$ 13.2	Kane (2007)	124
Gholipour et al. (2005)	145	Quassim et al. (2007)	110
Tlatov and Makarov (2005)	75 ± 10	Javaraiah (2007)	74
Jain (2006)	144	Hiremath (2007)	116
		This work	92.5 ± 4.6

11 yr (Damon and Jirikowic, 1992; Lockwood et al., 1999; Beer, 2000; Clilverd et al., 2003). These long trends can be related for periods longer than the 11-yr cycle such as the cycle Gleissberg, period of 80–80 yr, which presents a variation of amplitude in the cycle (Hathaway et al., 2002), a two-cycle variation with odd numbered cycles higher than the preceding even numbered cycles (the Gnevyshev–Ohl Effect) and a 205-yr cycle in radio isotope proxies, the Suess Cycle (Solanki et al., 2004). Long-term trends in solar activity have also been considered by other workers using proxy datasets such as C^{14} (Stuiver et al., 1998). Following a superposed epoch analysis of C^{14} data, Clilverd et al. (2003) suggested that cycle 24 would be similar to the previous cycles in amplitude, with low-activity levels not being reached until 2100 AD. This was mainly because of a 420-yr repetition of the low-activity conditions following the Maunder Minimum of 1700. In contrast, Usoskin et al. (2003) used Be^{10} analysis to suggest that we are currently in a prolonged period of exceptionally high solar activity with little suggestion of lower activity levels to come.

On the basis of earlier work by Sonett (1982), solar activity was modeled by Damon and Jirikowic (1992) as a low-frequency harmonic oscillator. In their analysis of C^{14} they developed a model with modulation of the 11-yr Schwabe carrier by longer periods (52.9, 88.1, 105.8 and 212.5 yr). The model results fitted well with the sunspot activity series from 1700 to 1970, although the authors noted that the activity minimum at the beginning of the 1900s was modeled poorly, possibly because of the need for even longer periods to be included.

This methodology presents very good results for sunspot number reconstruction and a good response for their prediction. However, due to the Waldmeier effect (Waldmeier, 1955), the prediction of cycles higher than the previous ones, presents large uncertainties as was the case for cycle 19, for which the method predicted that the mean annual number should have a maximum of 121.4 mean while the observed value was 190.0 (Fig. 6A). For solar cycles with smaller or equal sunspot number, the prediction was more precise as for cycle 20 with a predicted maximum sunspot number of 107.6 and an observed one of 105.9 (Fig. 6B).

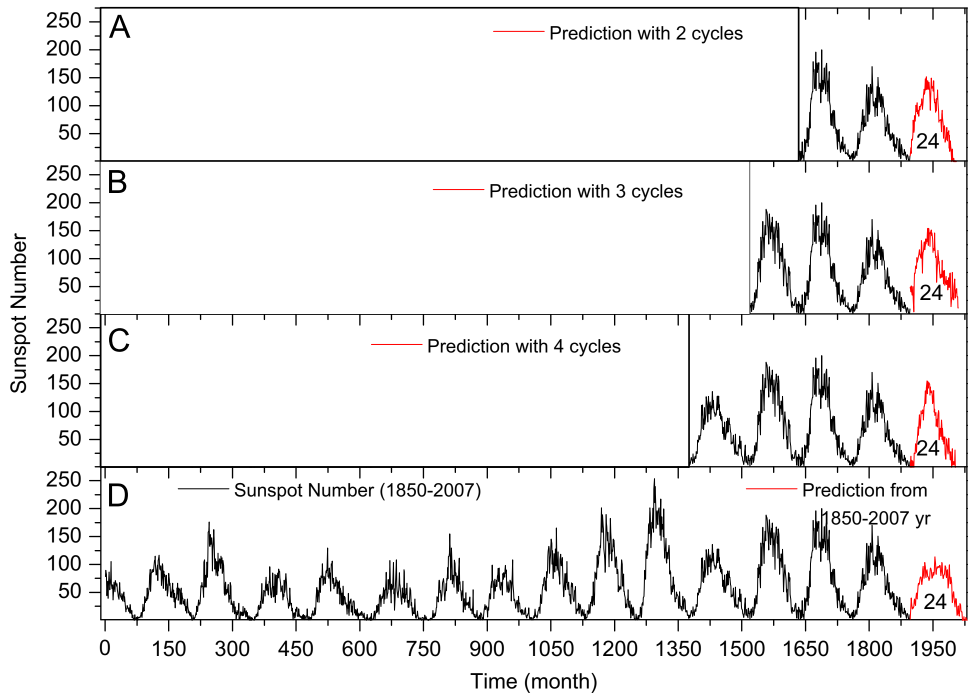

Fig. 5. Predictions of cycle 24 sunspot number using (A) two cycles (22 and 23), (B) three cycles (21–23), (C) four cycles (20–23) and (D) monthly sunspot number time series (1850–2007).

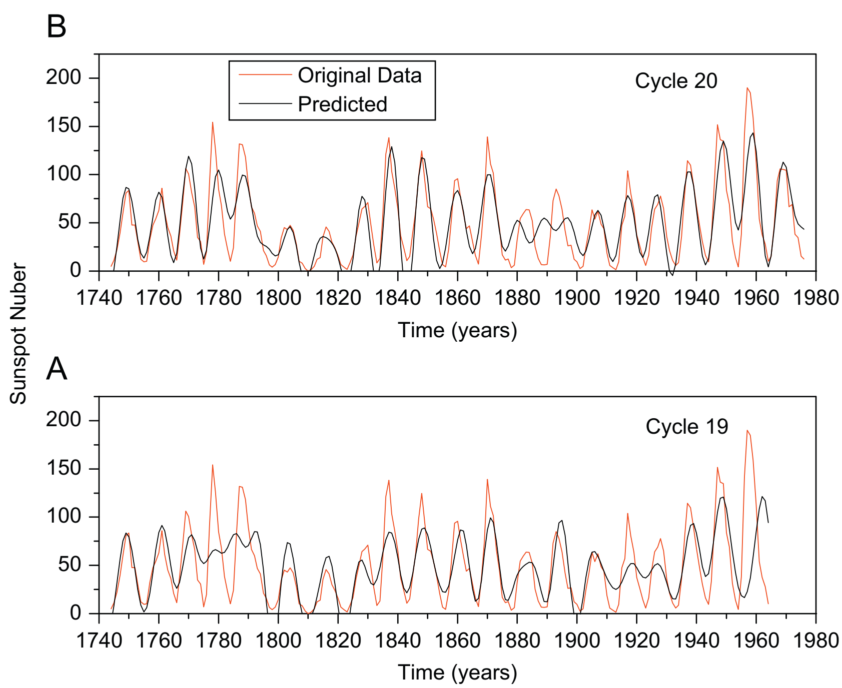

Fig. 6. (A) Predictions of cycle 19 using sunspot number time series for 1744–1954. (B) Predictions of cycle 20 using sunspot number time series for 1744–1964.

Errors that have been observed in this prediction scheme seem to be due to the limitation of the method itself and also because part of the nature (nonlinear features, Waldmeier effect) of the time series is not very well described by the model (Kane, 2008). It is important to comment that, although the solar cycle is asymmetric (e.g. fast rise and slow decline), the approximation of sine waves describes quite well the general behavior of solar activity (Echer et al., 2004). Also, the fact that by using different intervals the prediction could be different is a drawback of the method, but its accuracy in predicting solar maximum peak does not seem to be worse than that of the other methods (Kane, 2002).

The well-known Gnevyshev–Ohl (GO) rule (e.g., Gnevyshev and Ohl 1948; Wilson 1992; Storini and Sykora 1997) orders sunspot cycles to even–odd pairs so that intensity (sum of sunspot numbers over the cycle) of the odd cycle is larger than that of the preceding even cycle. If this trend continues in the future, then solar cycle 24 should be lower than cycle 23, which is consistent with the prediction presented in this work.

5. Conclusion

Reconstruction and prediction of sunspot number series were performed using a multiresolution combined with iterative regression analysis. Periodicities significant at 95% confidence level have been selected in order to reconstruct month and annual averages of the sunspot series during 1850–2007, with a correlation coefficient of $r=0.86$. The monthly mean sunspot number maximum prediction for cycle 24 was predicted to occur in November 2013 with a sunspot number of 113.3 and a length of 133 mo. The monthly mean sunspot number maximum prediction for cycle 25 was predicted to occur in April 2023 with a sunspot number of 132.1 and a length of 118 mo or 9.8 yr for the present solar cycle. Thus solar cycle 24 is predicted to be 23% lower than cycle 23 and cycle 25 5% lower than cycle 23 annual averages.

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