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Predicting Maximum Sunspot Number in Solar Cycle 24

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Abstract. A few prediction methods have been developed based on the precursor technique which is found to be successful for forecasting the solar activity. Considering the geomagnetic activity *aa* indices during the descending phase of the preceding solar cycle as the precursor, we predict the maximum amplitude of annual mean sunspot number in cycle 24 to be 111 ± 21. This suggests that the maximum amplitude of the upcoming cycle 24 will be less than cycles 21–22. Further, we have estimated the annual mean geomagnetic activity *aa* index for the solar maximum year in cycle 24 to be 20.6 ± 4.7 and the average of the annual mean sunspot number during the descending phase of cycle 24 is estimated to be 48 ± 16.8.

Key words. Sunspot number—precursor prediction technique—geomagnetic activity index *aa*.

1. Introduction

Predictions of solar and geomagnetic activities are important for various purposes, including the operation of low-earth orbiting satellites, operation of power grids on Earth, and satellite communication systems. Various techniques, namely, even/odd behaviour, precursor, spectral, climatology, recent climatology, neural networks have been used in the past for the prediction of solar activity. Many investigators (Ohl 1966; Kane 1978, 2007; Thompson 1993; Jain 1997; Hathaway & Wilson 2006) have used the 'precursor' technique to forecast the solar activity. Ohl (1966) noted that the geomagnetic activity in the declining phase of a sunspot cycle is found to be well correlated with the sunspot maximum of the next cycle. Using the geomagnetic activity *aa* index as the precursor, Jain (1997) predicted the maximum annual mean sunspot number for cycle 23 to be 166.2 which is found to be higher than the observed value of 120. In fact, he did not propose the error estimate in the predicted number otherwise it could have been within error limits.

In this view, we predict the maximum amplitude of solar cycle 24 using the precursor technique described by Jain (1997) in this paper. Section 2 describes about the acquisition of data of annual mean sunspot number and the geomagnetic activity *aa* index used in the current investigation. In section 3, we explain the analysis and results obtained. We briefly discuss and conclude our results in section 4 in the light of other investigations.

2. Data

There are several indices that are used as indicators of geomagnetic activity: Kp, Dst, *aa*, ap, Ap, and AE. The geomagnetic activity indices, *viz.*, Ap and *aa* are used as precursors to estimate the solar activity in future. In the present analysis, we exploit *aa* indices as geomagnetic precursor to estimate the maximum amplitude of upcoming solar cycle 24. These *aa* indices are derived using data from two nearly antipodal observatories, where magnetograms were available since 1868. The *aa* index represents the activity level at an invariant magnetic latitude of about 50°. The two observatories were Greenwich (1868–1925) in Northern Hemisphere and Melbourne (1868–1919) in Southern Hemisphere. Greenwich was replaced by Abinger in 1926 and by Hartland in 1957. Melbourne was substituted by Toolangui in 1920 and by Canberra in1980. The data is normalized by cross-correlation over the instruments distributed over the globe and over the time, and therefore may be considered homogeneous over the period under current study. The daily mean of the geomagnetic *aa* index has been obtained from http://isgi.cetp.ipsl.fr/ for the period 1868–2008.

The relative sunspot number (International Sunspot Number), Ri, is an index of the activity of the entire visible disc of the Sun. It is determined each day from an observing station without reference to preceding days using the form $Ri = K(10g + s)$, where g is the number of sunspot groups and s is the total number of distinct spots. The scale factor K (usually less than unity) depends on the observer and is intended to affect the conversion to the scale originated by Wolf. Therefore, the relative sunspot number Ri (international) is derived from the statistical treatment of data originating from more than twenty-five observing stations. The observed daily sunspot number for the period 1868–2008 was acquired from the following website http://www.ngdc.noaa.gov/stp/SOLAR/ftpsunspotnumber.html.

3. Analysis and results

3.1 *Prediction of the maximum annual mean sunspot number*

Considering the geomagnetic activity *aa* index as the precursor, the maximum amplitude of the solar cycle 24 is predicted using the method employed by Jain (1997). The temporal behaviour of observed annual mean sunspot number (red) and annual mean *aa* index (blue) for solar cycles 11 to 23 considered in our investigation is shown in Fig. 1. We observed from the figure that the annual mean *aa* index ranges from 5.7 (in 1901) to 36.6 (in 2003) which is an indicator of minimum and maximum geomagnetic activity respectively, during the period of 1868–2008. Whereas, the annual mean sunspot number varies between 1.4 (in 1913) and 190.2 (in 1957). Sunspot numbers rise steadily to maximum and then fall steadily to a low level during each sunspot cycle, whereas geomagnetic indices (Ap or aa) show two or more maxima per cycle, one near or before the sunspot maximum and others in the declining phase, and the gap between the two primary maxima (the Gnevyshev gap) results in the quasi-biennial and quasi-triennial periodicities observed in the geomagnetic indices (Kane 1997).

As the annual mean sunspot number for the year 2008 (until October) is 2.86, which is within the range of sunspot minimum value, we have considered the sunspot minimum year for solar cycle 23 to be 2008 in the present study. The annual mean *aa* index and annual mean sunspot number are obtained by averaging the monthly mean

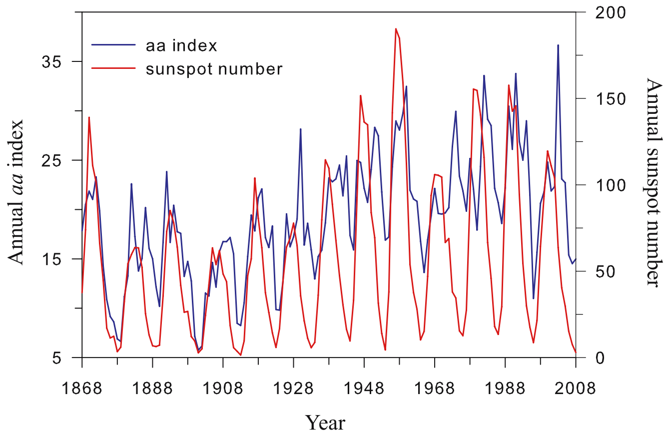

Figure 1. The observed annual mean *aa* index (blue) and annual mean sunspot number (red) for the period of 1868–2008. Note that the annual mean sunspot number for 2008 is 2.86.

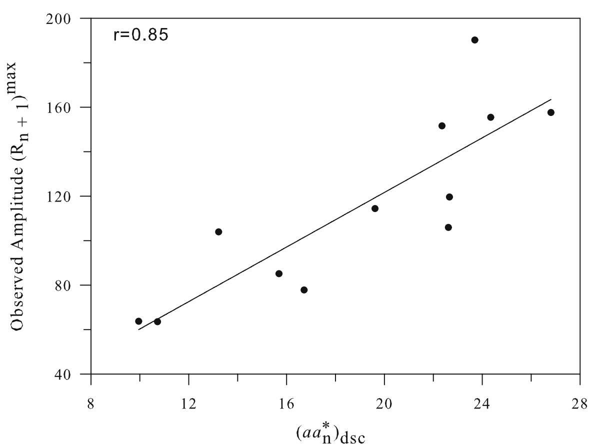

Figure 2. Observed amplitude $(R_{n+1})^{\max}$ is plotted against $(aa^*_n)_{\rm dsc}$. Correlation coefficient is found to be $r = 0.85$.

of geomagnetic activity index *aa* and monthly mean of sunspot number respectively for the period 1868–2008.

For nth cycle, we determined $(aa^*_n)_{\rm dsc}$, an average of the geomagnetic *aa* index, of the year in which observed sunspot is minimum and four years preceding to it (i.e., total 5 years). Then we compared $(aa^*_n)_{\rm dsc}$ of the nth cycle with the observed maximum annual mean sunspot number $(R_{n+1})^{\max}$ of $(n+1)$th cycle and obtained a relationship between $(aa^*_n)_{\rm dsc}$ and $(R_{n+1})^{\max}$ which is shown in Fig. 2. The best linear fit to the data with the correlation coefficient of 0.85 led us to derive an asymptotic relation as follows:

$$(R_{n+1})^{\max} = 6.138(aa^*_n)_{\rm dsc} - 1.1. \tag{1}$$

Using relation (1), we have obtained the maximum annual mean sunspot number for cycles 12 to 23, which are almost in agreement with the observed values. The standard

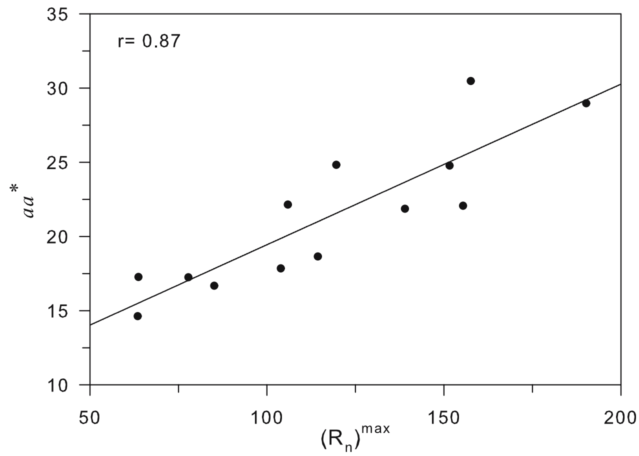

Figure 3. Representation of observed values of aa^* as a function of $(R_n)^{\max}$ of the same cycle. Correlation coefficient is 0.87.

deviation $\sigma = \pm 21$ is found from the difference between the calculated and observed values. The relation (1) enabled us to predict the maximum annual mean sunspot number for cycle 24 $(R_{23+1})^{\max}$ to be 111 ± 21. This suggests that the maximum amplitude will be less than that of cycles 21–22. Our prediction of the maximum amplitude is in good agreement with the predictions made by a few earlier investigators (Wang *et al.* 2002; Echer *et al.* 2004; Dabas *et al.* 2008; Hiramath 2008; Javaraiah 2008) while in contrast to Hathaway and Wilson (2006).

3.2 *Prediction of the annual mean geomagnetic activity index for the solar maximum year*

Next, in order to predict the level of geomagnetic activity for the sunspot maximum year in cycle 24, we obtained aa^*, which is the annual mean of aa during the year when sunspot is maximum for each cycle 11–23. And then the relation between the observed $(R_n)^{\max}$, and aa^* is studied. Figure 3 represents the relationship between $(R_n)^{\max}$ and aa^* for a given cycle. A linear fit is obtained between the two with a correlation coefficient of ~ 0.87 which can be expressed as:

$$aa^* = 0.1082(R_n)^{\max} + 8.6158. \tag{2}$$

Using the above relation, we predicted aa^* for each cycle 11–23, which is in good agreement with the observations. Considering the predicted amplitude of cycle 24 to be 111 ± 21 (section 3.1), it enabled us to estimate the aa^* during the sunspot maximum year for the cycle 24 to be 20.6 ± 4.7. This predicted value of aa^* is lower compared to the observed 30.47 and 24.82 for cycle 22 and 23 respectively. This depicts the decreasing trend of geomagnetic activity during the sunspot maximum year of the upcoming cycle 24 as compared to previous two cycles.

Table 1. Period of descending phase and the corresponding average of observed annual mean sunspot number for solar cycles 11 to 23.

Sunspot cycle	Descending phase	$(\overline{R}_n)_{\rm dsc}$
11	1871–1878	46
12	1884–1889	28
13	1894–1901	33
14	1906–1913	30
15	1918–1923	38
16	1929–1933	28
17	1938–1944	53
18	1948–1954	68
19	1958–1964	84
20	1969–1976	56
21	1980–1986	79
22	1990–1996	70
23	2001–2008	47

3.3 *Prediction of average of the annual mean sunspot number during the descending phase*

Further, we have predicted $(\overline{R}_{24})_{\rm dsc}$, the average of annual mean sunspot number of the descending phase for solar cycle 24. The descending phase is defined as the period from the year following the sunspot maximum to the year of sunspot minimum for a solar cycle. We determined the average of annual mean sunspot number of the descending phase, $(\overline{R}_n)_{\rm dsc}$ for each cycle from 11 to 23 using the following relation:

$$(\overline{R}_n)_{\rm dsc} = \frac{1}{j}\sum_{i=1}^{j}, R_i$$

where $i = 1, 2, \ldots, j$, and j is the number of years in the descending phase, and R_i is the annual mean of sunspot number. The period of descending phase for solar cycles 11 to 23 and the corresponding $(\overline{R}_n)_{\rm dsc}$ are given in Table 1.

We found that the $(\overline{R}_n)_{\rm dsc}$ of a given solar cycle is well related to the maximum annual mean sunspot number $(R_n)^{\rm max}$ for that cycle as shown in Fig. 4. The linear fit with a statistically significant correlation coefficient of 0.93 is obtained which can be expressed in the form of an empirical relation:

$$(\overline{R}_n)_{\rm dsc} = 0.4651(R_n)^{\rm max} - 4.0141. \tag{3}$$

Using relation (3), the average of the annual mean sunspot number during the descending phase for cycles 11 to 23 is calculated and the standard deviation σ determined from the difference of the observed and predicted value is found as ± 7. The relation (3) enabled us to estimate $(\overline{R}_{24})_{\rm dsc}$ to be 48 ± 16.8 (considering error ± 21

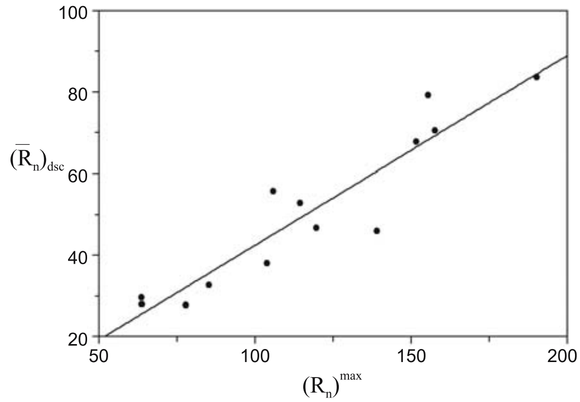

Figure 4. $(\overline{R}_n)_{\text{dsc}}$ is plotted against $(R_n)^{\max}$ for solar cycles 11 to 23. Correlation coefficient is found to be remarkable and is 0.93.

in estimate of $(R_{24})^{\max}$) which is comparable to the observed annual mean sunspot number during the descending phase of cycle 23 (*cf.* Table 1). This also suggests that the sunspot activity during the descending phase of the upcoming solar cycle 24 will decline by about 30–40% as compared to the cycles 18, 19, 21 and 22 (*cf.* Table 1).

4. Discussion and conclusion

In the current investigation we have predicted maximum amplitude of annual mean sunspot number of upcoming solar cycle 24 to be 111 ± 21 by the 'precursor technique' using the long term data since 1868 to 2008. Further, we predicted annual mean *aa* index for the sunspot maximum year to be 20.6 ± 4.7. The average of annual mean sunspot number during the descending phase is estimated to be 48 ± 16.8, when the error of ± 21 in $(R_{24})^{\max}$ is considered.

The following investigators have used various techniques to determine the maximum amplitude of annual mean sunspot number for solar cycle 24 and are in agreement with our prediction. Javaraiah (2008) has predicted the amplitude of upcoming cycle 24 to be 103 ± 10 (or 87 ± 7) using the north–south asymmetry in the area sum of the previous cycle. Using a modified precursor method, Dabas *et al.* (2008) have predicted the maximum amplitude of about 124 ± 23. Hiramath (2008) predicted the amplitude of cycle 24 to be 110 ± 11 using the physical parameters (long-term amplitudes, frequencies, phases, decay factor) of the previous 22 solar cycles and by an autoregressive model. On the basis of extrapolation of sunspot number spectral components, Echer *et al.* (2004) have predicted the maximum to occur in 2012 (115 ± 13.2) or to occur in 2013 (117 ± 13.2). Wang *et al.* (2002) made a preliminary prediction of 83.2–119.4 for the maximum amplitude of cycle 24 using statistical characteristics of solar cycles which is in agreement with our prediction.

Based on Ohl's precursor method, Kane (2007) has given a preliminary prediction of Rz (max) to be 142 ± 24 (or 124 ± 26, if *aa* values are in error by 3 nT before 1957). Hathaway & Wilson (2006) based on the analysis of geomagnetic *aa* indices predicted the peak smoothed sunspot number to be 160 ± 25, which is higher than our prediction. The difference in prediction is due to the technique employed by Hathaway & Wilson

(2006) and ours. They considered the smoothed interplanetary component of the *aa* index which peaked in October 2003 whereas we have taken the annual mean of *aa* index from January 2004 to September 2008 from the descending phase of cycle 23, when the geomagnetic activity was low.

Many investigators have used different techniques to find the upcoming solar cycle 24. According to Dikpati *et al.* (2006), the upcoming cycle 24 will be about 30–50% stronger ($R_z = 155$–180) using modified flux transport solar dynamo model and the data of sunspot area. Choudhuri *et al.* (2007) modelled the last few solar cycles by 'feeding' observational data of the Sun's polar magnetic field into their solar dynamo model. They predict that cycle 24 will be about 35% weaker than cycle 23.

We conclude that our prediction of maximum amplitude, annual mean *aa* index for the sunspot maximum year and average of annual mean sunspot number during the descending phase of solar cycle 24 will hold good.

Acknowledgements

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