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Prediction verification of solar cycles 18–24 and a preliminary prediction of the maximum amplitude of solar cycle 25 based on the Precursor Method

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Abstract Predictions of the strength of solar cycles are important and are necessary for planning long-term missions. A new solar cycle 25 is coming soon, and the amplitude is needed for space weather operators. Some predictions have been made using different methods and the values are drastically different. However, since 2015 July 1, the original sunspot number data have been entirely replaced by the Version 2.0 data series, and the sunspot number values have changed greatly. In this paper, using Version 2 smoothed sunspot numbers and aa indices, we verify the predictions for cycles 18–24 based on Ohl's Precursor Method. Then a similar-cycles method is used to evaluate the aa minimum of 9.7 ($\pm$1.1) near the start of cycle 25 and based on the linear regression relationship between sunspot maxima and aa minima, our predicted Version 2 maximum sunspot number for cycle 25 is 121.5 ($\pm$32.9).

Key words: solar cycle — sunspot — geomagnetic aa indices

1 INTRODUCTION

The prediction of solar activity and especially of the sunspot cycle magnitude and timing is one of the most important active fields in space weather research. Solar activity variations cause changes in interplanetary and near-Earth space. In turn, these affect the operation of space-borne and ground-based technological systems (space flights, navigation, radars, high-frequency radio communications, ground power lines, etc.). Space weather operators use solar activity predictions to estimate orbit drag, to plan when to re-boost satellites in low Earth orbit, and to anticipate radiation exposure for upcoming mission. These facts justify the scientific and practical importance of the prediction of solar cycle strength in advance.

Nowadays, the great challenge for space science is to predict the characteristics of the solar cycle, e.g., predicting the solar activity during a solar cycle using sunspot series that are already available. To predict the amplitude of a solar cycle, many methods are suggested. For cycle 24, Pesnell (Pesnell 2012) compiled 75 predictions and these predications were placed into categories of climatology, recent climatology (after solar cycle 17), precursor, dynamo model, spectral, neural network, and stock market and economic indicator prediction methods. The prediction values have a wide range of 42 to 185. Climatological forecasts assume that the future of a system can be determined from the statistical properties of the past and a large number of forecasts in this category show the utility of climatological forecasts. Precursor forecasts, the leading indicators of solar activity through solar minima, remain the most common category of predictions. Brown (Brown 1986), Hathaway, Wilson, and Reichman (Hathaway et al. 1999), and Li, Yun and Gu (Li et al. 2001) showed that climatological class of predictions was less accurate than the precursor class for the last few solar cycles. Among these precursor methods, the polar field and geomagnetic index are two precursors which have received the most attention. Geomagnetic variations during the solar minima are potentially caused by the solar polar field by the connection of the solar open flux (Jiang et al. 2007; Jiang 2013). Models of the Sun's magnetic dynamo suggest that the Sun's largely dipole magnetic field at cycle minimum is the seed of the magnetic field that erupts in the form of sunspots after application by the Sun's differential rotation (Babcock 1961; Leighton 1969). Wang and Sheeley (Wang & Sheeley 2009) have noted that the strength of the Sun's axial dipole is more closely attuned to the dynamo theory and may be measured more accurately than the polar fields for previous cycles. The axial dipole largely determines the interplanetary magnetic field near cycle minima and this field can be derived from historical geomagnetic measurements (Svalgaard & Cliver 2005; Rouillard et al. 2007). In fact, Wang and Sheely (Wang & Sheeley 2009) suggest that it is this connection that makes the geomagnetic aa index at its minimum such a good predictor for the amplitude of the following cycle (Ohl 1966). Since then, Brown and Williams (Brown & Williams 1969), Kane (Kane 1978, 1987, 1992, 2007), and Wilson (Wilson 1988, 1992) have been studying this aspect over recent decades.

In this paper, we will apply a geomagnetic precursor method (Ohl's Precursor Method) to predict the amplitude of the coming solar cycle 25. In Section 2, using new revised sunspot numbers (Version 2), we discuss the verification of predictions based on a geomagnetic precursor method (Ohl's Precursor Method) for previous cycles. In Section 3, firstly we use a similar-cycles method to predict aa minima, and then use Ohl's Precursor Method to predict the maximum amplitude of the coming cycle 25.

2 VERIFICATION OF THE PREDICTIONS

For geomagnetic precursor methods, aa index is not the only parameter to be used. In the summary of predictions of solar cycle 24 (Pesnell 2012), there were 16 predictions based on geomagnetic precursor methods. Nine predictions used aa index as their indicator of geomagnetic activity, six used Ap index and one used both. Similarly to the Ap index, the aa index is also a description to measure the amplitude of global geomagnetic activity during 3-hour intervals normalized to geomagnetic latitude $\pm 50°$; aa was introduced to monitor geomagnetic activity over the longest possible time period using two antipodal magnetic observatories from 1868 onwards, while the Ap index is from 1932. Long-term observations of aa index provide larger amounts of data for studying the relationship between sunspots and geomagnetic activity. In this study, 13-month smoothed aa indices and Version 2.0 13-month smoothed sunspot numbers are used (aa data are from `http://isfi.unistra.fr`, and sunspot data are from `http://www.sidc.be`), and 13-month smoothed aa values and sunspot numbers are defined by Equation (1):

$$\overline{M_i} = \frac{1}{12}[\frac{1}{2}(M_{i-6} + M_{i+6}) + \sum_{j=i-5}^{i+5} M_j], \qquad (1)$$

where M_i is the monthly aa value or monthly sunspot number for month i.

Svalgaard and Cliver (Svalgaard & Cliver 2007) show that the earlier aa index data are offset from the later data with a shift occurring abruptly in 1957 when the English geomagnetic observatory was moved from Abinger to Hartland. This offset can be corrected by adding three units to all aa index data prior to 1957. In this paper, 3 nT has been added to the pre-1957 aa values to create a new data set. Figure 1 shows plots of the 13-month smoothed sunspot numbers (Version 2.0) and aa indices of solar cycles 12 to 24. It can be seen that the number of sunspots varies regularly and each solar cycle can be visually distinguished from the map. Sunspot maxima are marked by dots and aa minima by asterisks. The variation of the geomagnetic aa indices are much more complex, and several peaks appear in one cycle. But, it can be seen that geomagnetic aa minima during the solar minimum phase are well correlated with the succeeding sunspot maxima.

In order to apply the geomagnetic precursor method better to predict the amplitude of cycle 25, firstly we evaluate the predicted results of the historical solar cycles based on the geomagnetic precursor method. Figure 2 shows the plots and the regression lines of aa minima ($aa_{\rm min}$) during minimum phase of a solar cycle and the following sunspot number maximum ($R_{\rm max}$) several years later for cycle 17 onward. It can be seen that in Figure 2(a), the correlation coefficient is only 0.53 because there are only five solar cycles used (cycles 12–16), and then points are well correlated for Figures 2(b)–2(h). The correlation of cycles 12–20, cycles 12–21, cycles 12–22 and cycles 12–23 is stable at 0.92. So how accurate are the predictions of the maximum value of these solar cycles when using the fitting relationship between these sunspot number maxima and aa minima? Table 1 gives the results from cycle 18 and the errors between the prediction and the observation. That is to say, the linear regression equation obtained from points of cycles 12–17 is used to predict $R_{\rm max}$ (18) of cycle 18, and the linear regression equation obtained from points of cycles 12–18 is used to predict $R_{\rm max}$ (19) of cycle 19, and so on. From comparisons between the predicted and observed values for cycles 18–24, we can see that the predictions are higher than the observations for cycle 18 and cycles 20–23. The predictions are lower than the observations for cycle 19 and cycle 24, especially for cycle 19. The predicted values of cycles 18 and 22 are very good.

3 PREDICTION OF CYCLE 25

Having evaluated the predictions based on the geomagnetic precursor method, in this section, we use this method to predict the maximum value of solar cycle 25. Figure 3 shows the plots and the fitting line for cycles 12–24. The correlation coefficient is 0.92 and the linear regression Equation (2) is obtained with a mean standard error of 19.9. From the sunspot number maxima ($R_{\rm max}$) of all cycles, it can be seen that cycle 19 is the strongest in history with an $R_{\rm max}$ of 285 and that the $R_{\rm max}$ has a large deviation from the fitting line:

$$R_{\rm max} = 11.9 aa_{\rm min} + 6.27\,. \qquad (2)$$

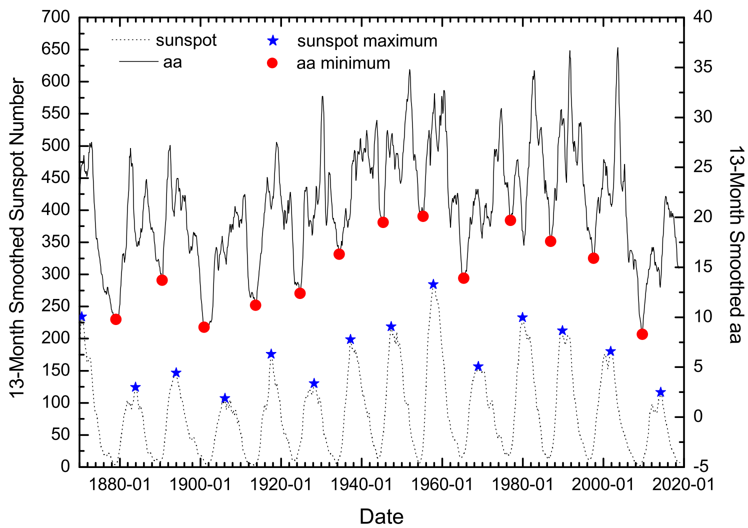

Fig. 1 Plots of the 13-month smoothed sunspot numbers (Version 2) and aa indices of solar cycles 12 to 24 (sunspot maxima are marked by *asterisks* and aa minima by *dots*).

Table 1 Comparisons between Observation and Prediction of Sunspot Number Maximum ($R_{\rm max}$)

Cycle	$a_{\rm min}$	$R_{\rm max}$ (obs.)	$R_{\rm max}$ (pre.)	Error (%)
12	9.6	124.4		
13	13.6	146.5		
14	8.9	107.1		
15	11.2	175.7		
16	12.2	130.2		
17	16.1	196.6		
18	19.3	218.7	220.4	+1.7(0.8%)
19	19.8	285.0	224.3	−60.7(21.3%)
20	13.7	156.6	171.3	+14.7(9.4%)
21	19.5	232.9	244.1	+11.2(4.8%)
22	17.4	212.5	214.9	+2.4(1.1%)
23	15.7	180.3	193.4	+13.1(7.2%)
24	8.3	116.4	102.6	−13.8(11.9%)

Then, to predict the sunspot number maximum for cycle 25 using Equation (1), the key factor is the aa minima. Have aa indices reached its minimum? Table 2 shows the smoothed aa values from Jan. 2018. It can be seen that as of November 2018 (the latest observation), the observations have been declining. Figure 4 shows plots of the time lag in months between aa minimum occurrence time and the beginning of the corresponding solar cycle. This shows that only for cycle 14 did the aa minimum occur before the cycles beginning. For other cycles, the aa minimum often occurred 0–14 months (with a mean of 6 months) after the solar cycle began. For example, solar cycle 24 began in December 2008 and the aa minimum occurred in September 2009. Presently (7/2019), solar activity and geomagnetic activity are low and still declining. Both have not yet reached their minimum. So, what is the value of the aa minimum?

Table 2 Smoothed aa Indices from Jan. 2018

Date	Smoothed aa index
2018–01	17.9
2018–02	17.5
2018–03	16.9
2018–04	16.1
2018–05	15.6
2018–06	15.2
2018–07	15.1
2018–08	15.1
2018–09	15.0
2018–10	14.9
2018–11	14.8
2018–12	14.6

Wang (1992) proposed the similar cycle method, in that similar cycles have similar characteristic parameters and cycle profiles, and used it in prediction of cycles 22 and 23. Upton and Hathaway (Upton & Hathaway 2014) noted that solar cycle 14 matched the amplitude and profile of cycle 24 and simulated the axial dipole moment with cycle 14 active regions to predict the timing of the reversal. For cycle 24, by comparing cycles 1–23 with cycle 24, it can be seen that cycle 12 and cycle 14 are the most similar to cycle 24. Figure 5 show plots of these three cycles. The three cycles have a similar beginning and similar amplitude and cycle profiles. In this section, we try to apply this similar method to aa indices. Figure 6 shows the monthly aa indices, the smoothed aa indices of cycles 12, 14 and 24, and the mean aa indices of cycle 12 and cycle 14. The monthly values of aa indices vary erratically from month to month. For smoothed aa indices, the maximum strengths of the three cycles are different because of the randomness of solar eruption especially during a solar maximum phase. But the trends are similar, and the profiles of the smoothed aa

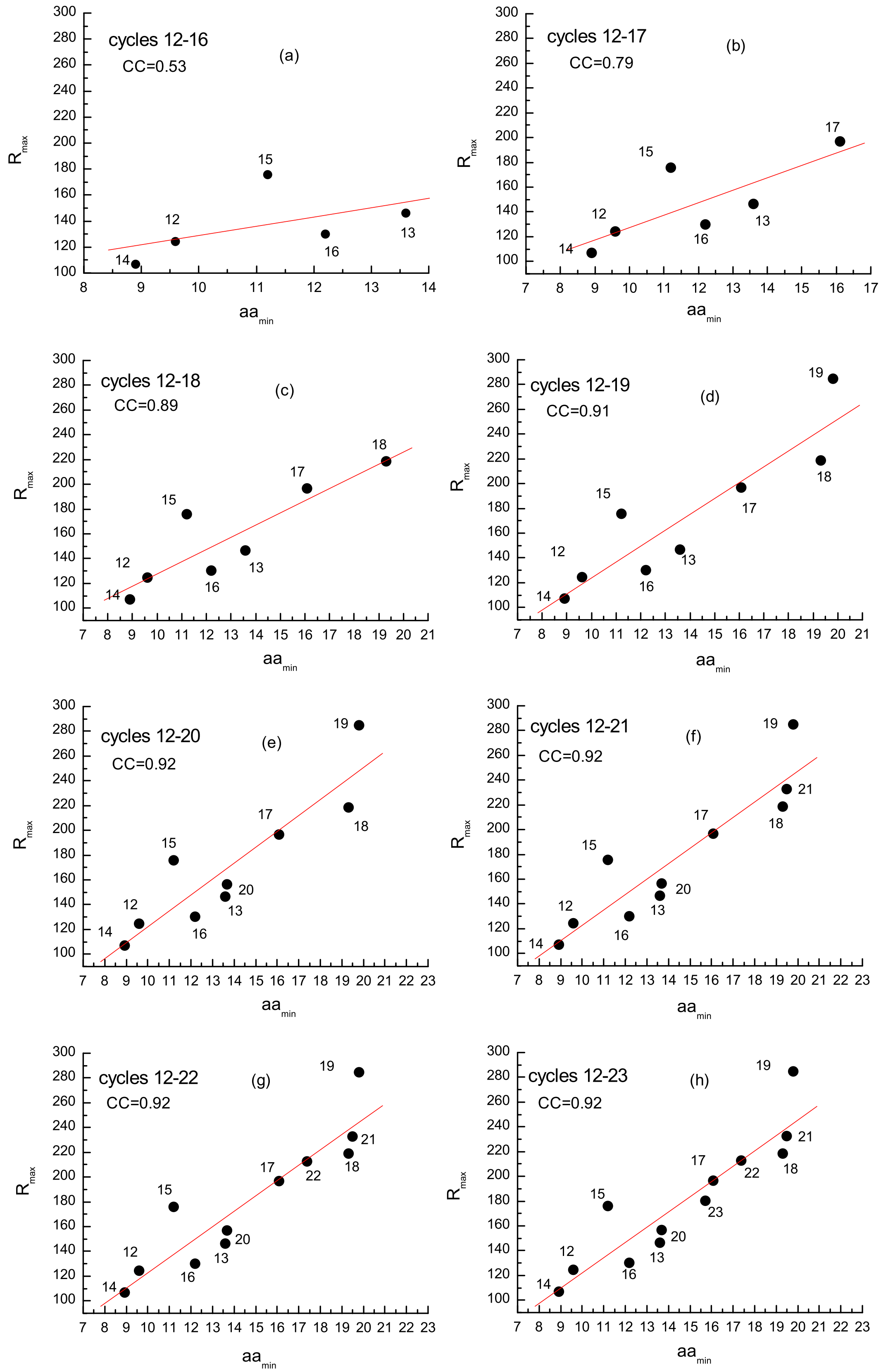

Fig. 2 Plots of the 13-month smoothed sunspot numbers (Version 2) and aa indices of solar cycles 12 to 24.

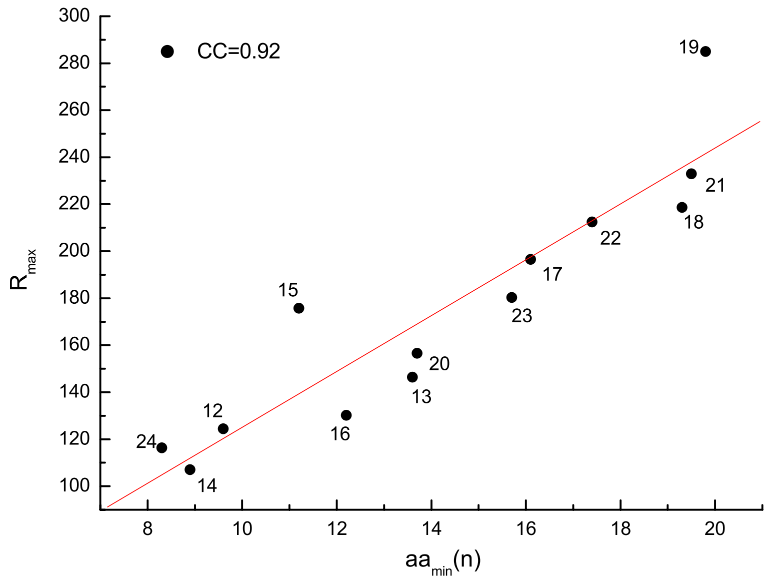

Fig. 3 Plots of geomagnetic aa minimum and the succeeding sunspot number maximum for cycles 12 to 24.

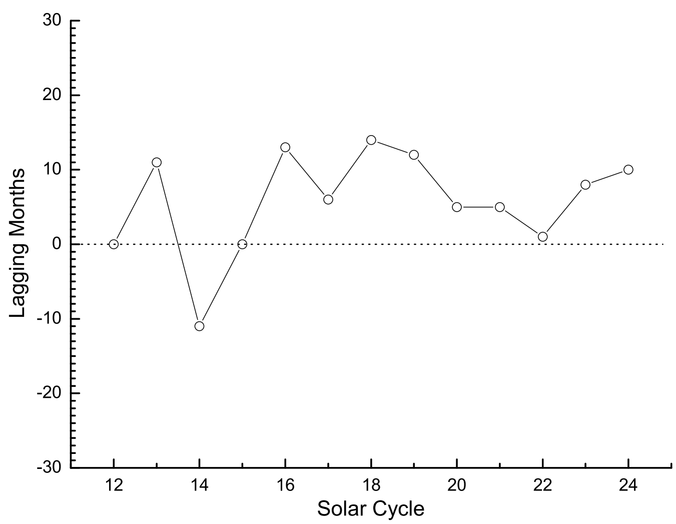

Fig. 4 Lagging months between aa minimum occurrence time to the cycle start time for cycles 12–24.

of cycle 24 and the mean aa values are similar. Hence, we use mean aa values as predictions for November 2018 onward and the predicted aa minima may be 9.7 with a mean error of 1.1. So using $aa_{\min}$ =9.7($\pm$1.1) for the beginning of cycle 25, the sunspot maximum value of cycle 25 is expected to be 121.5($\pm$13.0) using Equation (2). Considering the mean standard error of 19.9 for Equation (1), the amplitude of cycle 25 is estimated to be 121.5($\pm$32.9) for the Version 2 sunspot number, a slightly higher value than the 116.4 of cycle 24.

For cycle 25, many predictions have been made and they give different values. Abdusamatov (Abdusamatov 2007) and Javaraiah (Janardhan et al. 2015) made a prediction of about 50. Hathaway and Wilson (Hathaway & Wilson 2004) gave a prediction of 70. Pishkalo (Pishkalo 2008) predicted 112.3 ± 33.4, and Quassim and Attia (Quassim et al. 2007) predicted 116. Hamid and Galad (Helal & Galal 2013) predict the peak of 118. Du (Du 2006; Du & Du 2006; Du et al. 2006) gave three values, 102 ± 22.4, 116$\pm$17.4 and 144$\pm$27.6. Pesnell and Schatten (Pesnell & Schatten 2018) combined solar polar magnetic field and F10.7 to create a new precursor index SODA and predict the Version 2 sunspot number of 135 ± 25. Javaraiah (Javaraiah 2017) gave another prediction value of 29.9 ± 10. Upton and Hathaway (Upton & Hathaway 2014) use a flux transport mode to predict solar polar magnetic field and the results suggest solar cycle 25 might be similar in size to cycle 24. Janardhan (Janardhan

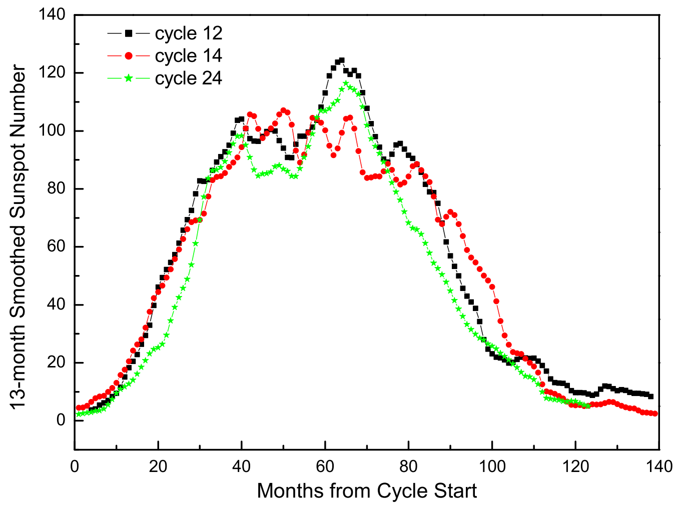

Fig. 5 Profile of cycles 12, 14 and 24.

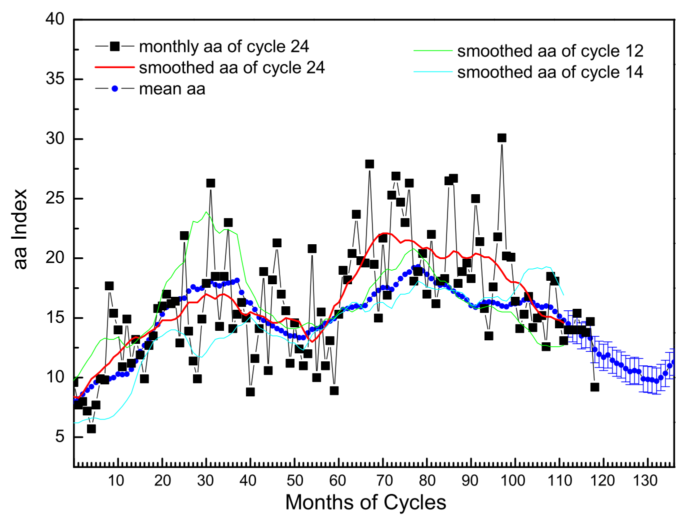

Fig. 6 Monthly and smoothed aa indices of cycle 24, and the corresponding aa indices of cycle 12 and cycle 24 and mean aa values.

et al. 2015) used the correlation between the polar field and the hemispheric magnetic field at solar minimum to estimate that the peak sunspot number for solar cycle 25 is likely to be 62 ± 12. Hathaway and Upon (Hathaway & Upton 2016) used a surface flux transport model to predict the amplitude and hemispheric asymmetry of solar cycle 25, and the results showed that cycle 25 would be a small cycle like cycle 24. Cameron and Jiang (Cameron et al. 2016) gave the expected dipole moment to be around 2020 (2.5 ± 11 G) and suggested cycle 25 will be of moderate amplitude, not much higher than that of the current cycle. Wang (Wang 2017) discussed the relationship between surface flux transport and polar field evolution, and predicted that cycle 25 will be similar in amplitude to cycle 24. Okoh, Seemala and Rabiu (Okoh et al. 2018) used a hybrid regression-neural network method to predict the maximum SSN to be 122.1 ± 18.2. Jiang (Jiang et al. 2018) developed a scheme to investigate the predictability of the solar cycle over one cycle and the maximum strength is expected to lie in the range 93–155. Table 3 shows the different predictions for cycle 25. Most predictions are made using Version 1 sunspot values before 2015–2016 and they are multiplied by approximately 1.5 for comparison with the predictions of values using Version 2.0. In Table 3, these $R_{\rm max}$ are marked by asterisks.

4 CONCLUSIONS AND DISCUSSION

Sunspot number is usually used as an index of solar activity, which shows a predominantly 11-year cycle. In the

Table 3 Predictions of Solar Cycle 25 ($R_{\max}$ converted from Version 1 are marked by asterisks)

Author and date	Predicted $R_{\max}$ (Version 1)	Predicted $R_{\max}$ (Version 2)	Year of Maximum
Chistyakov (1983)	121	181.5*	2028.5
Kontor et al. (1983)	117	175.5*	2024
Hathaway & Wilson (2004)	70±30	105±30*	2023
Du (2006)	102.6±22.4	153.9±22.4*	
Du & Du (2006)	111.6±17.4	167.4±17.4*	
Du et al. (2006)	144.3±27.6	216.5±27.6*	
Abdusamatov (2007)	50±15	75±15*	
Quassim et al. (2007)	116	174*	2020
Hiremath (2008)	110±11	165±11*	75±0.7
Pishkalo (2008)	112.3±33.4	168.5±33.4*	4–6/2023
Rigozo et al. (2011)	132.1	75198.2*	2023.04
Attia et al. (2013)	90.7±8	136.1±8*	2020
Javaraiah (2015)	50±10	75±10*	
Upton & Hathaway (2014)	Similar to cycle 24	Similar to cycle 24	
Helal & Galal (2013)	118	177*	
Li et al. (2015)	109.1	163.7*	2023.75
Janardhan et al. (2015)	62±12	93±12*	
Hathaway & Upton (2016)	Similar to cycle 24	Similar to cycle 24	
Obridko & Shelting (2016)	50	75*	
Javaraiah (2017)	29.9±10	44.9±10*	
Wang (2017)	Similar to cycle 24	Similar to cycle 24	
Pesnell & Schatten (2018)		135±25	
Okoh et al. (2018)		122.1 ± 18.2	2025(±6 month)
Jiang et al. (2018)		93–155	

present satellite age, the strength of the solar cycle significantly affects satellite operators, who plan their launches many years in advance. Hence, solar cycle predictions are needed to plan long-term space missions, just as weather predictions are needed to plan the launch.

For solar cycle 25, predictions have been made using different methods and the values have a wide range from 30 to 144. For sunspot values, since 2015 July 1, the original sunspot number data have been entirely replaced by a revised data series (Version 2.0) and the original version will not be maintained and extended anymore. Previous methods and results may need to be reassessed.

In this study, Version 2.0 sunspot numbers and aa indices are used. Firstly, we evaluate the predictions for cycles 18–24 based on a geomagnetic precursor method. For the geomagnetic precursor method, the aa minimum is a key parameter. Comparing the time of aa minima and the start times of the corresponding solar cycles, the aa minima often occur 0–14 months (with a mean of 6 months) after a solar cycle starts. Presently (2019), solar activity and geomagnetic activity are very low, but they may have not reached their minima. In this study, we use a similar-cycles method and selecting cycles 12 and 14 as the most similar cycles to cycle 24. The mean aa values of cycle 12 and cycle 14 accord well with the observed values. Hence, the mean aa values can be used as preliminary predictions for December 2018 onward and the predicted aa minimum may be 9.7(±1.1). Then we obtain the predicted sunspot value of cycle 25 is to be 121.5(±13.0). Considering the mean standard error of 19.9, we predict the preliminary amplitude for cycle 25 to be 121.5 ± 32.9 (Version 2), a slightly higher than cycle 24. In terms of geomagnetic precursor method, a more accurate prediction may be given when the aa minimum is realized.

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