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Prediction of the smoothed monthly mean sunspot numbers for solar cycle 24

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The prediction for the smoothed monthly mean sunspot numbers (hereafter SMSNs) of solar cycle 23, which was given with a similar cycle method proposed by us at the beginning time of cycle 23, is analyzed and verified in this paper. Using our predicted maximum SMSN and the ascending length for solar cycle 24, and assuming their relative errors to be respectively 20% and ± 7 months, solar cycles 2, 4, 8, 11, 17, 20 and 23 are selected to be the similar cycles to cycle 24. The selected solar cycles are divided into two groups. The first group consists of all the selected cycles; while the second group consists of only cycles 11, 17, 20 and 23. Two SMSN time profiles then may be obtained, respectively, for the two similar cycle groups. No significant difference is found between the two predicted time profiles. Considering the latest observed sunspot number so far available for cycle 23 and the predictions for the minimum SMSN of cycle 24, a date calibration is done for the obtained time profiles, and thus, SMSNs for 127 months of cycle 24, from October 2007 to April 2018, are predicted.

solar cycle, sunspot numbers, prediction of cycle 24

A Wolf sunspot number, or the so-called relative sunspot number, is usually used as one of the solar indices describing solar activity, which is made of the number of sunspots and the number of sunspot groups[1]. The number is obviously lack of physical meanings compared, for examples, with the solar flux at 2800 MHz, the total area of sunspots[2] , and the group sunspot number[3]. The relative sunspot number has a historical record longer than 200 years, its time sequence reflects clearly the periodicities of solar activity[4], and the number has close relations with the productivities of solar activities such as solar flares[5] and coronal mass ejections[6,7]. So, the number is used in the fields of solar physics, geophysics and space weather more frequently than other indices. The Wolf number is often simply called sunspot number. However, in studies and predictions of long-term variations of solar activities, the smoothed monthly mean sunspot number (hereafter

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SMSN) is always used. The extrema and phases of a solar cycle (i.e. sunspot cycle, or sometimes a solar activity cycle) are determined by the SMSN, as an international tradition. Hence, SMSNs are the main objects of solar cycle predictions.

Now we are in the tail of solar cycle 23. Predicting the SMSNs for cycle 24 should be one of our tasks we are facing. In recent decades, progresses have been made in the methodology research for solar cycle predictions. Most of the studies are focused on the prediction of the parameters of a solar cycle, namely predicting amplitudes and times of the extrema of the next cycle[8]. Brown[9] and Kunches[10] reviewed the predictions for solar cycles 21 and 22, respectively. Their results showed that generally, methods using precursors produced the predictions better than those given by methods using the statistical property of solar cycles. Thompson[11] pointed out that the only prediction methods, which have approval from most of the scientific community, are the "precursor" techniques. Li et al.[12] compared 63 predictions of the maximum SMSN for cycle 22 and 48 predictions for cycle 23 and pointed out that precursor methods are superior, and inferred that the peak SMSN of cycle 23 should be 162. A prediction of 119 for the maximum SMSN of cycle 23 was made in 1992 by Wang[13] using the cycle statistical method, which is very near 120.8, the observed maximum SMSN of cycle 23 (relative error approximate 1.5%). Wang et al.[14] predicted the maximum SMSN for cycle 24 to be in the range of 83—119, using again the similar cycle method, and pointed out that in recent decades there has not been a method which was able to produce reasonably good predictions for solar cycles 21, 22 and 23, and thus the solar cycle prediction was still an open problem.

Compared with the prediction of solar cycle parameters, the prediction of SMSNs of individual months for a cycle, in particular for the next cycle, would be of more use for the operation of space technique, communications, etc. Wang and Han[15,16] proposed a similar cycle method based on the conception that, generally, we may find not only one but more cycles similar to a certain solar cycle. The application of the method to cycle 23 results in very successful predictions of SMSNs (errors $\leqslant$ 30%) for the 96 months from August 1996 to July 2004[17,18]. Several methods have been used to make this kind of prediction and Li et al.[19] proposed a method for the prediction of SMSNs for the remainder of a progressing solar cycle. They found that cycle 2 is the similar cycle of cycle 23.

Two purposes of this work are: (1) predicting the SMSNs of cycle 24, from 2007 to 2018; and (2) trying to develop an applicable and feasible method for SMSN predictions of the next cycle.

1 Similar cycle method and verification of the prediction of SMSNs for cycle 23

As mentioned above, the predicted quantity is the SMSN in a solar cycle prediction, which is indicated by $\overline{R}_i$ and defined by eq. (1):

$$\overline{R}_i = \frac{1}{12}\left[\frac{1}{2}(R_{i-6} + R_{i+6}) + \sum_{j=i-5}^{i+5} R_j\right], \tag{1}$$

where R_i is the observed monthly mean sunspot number for month i. In the following parts, we will use $\overline{R}_{\min}$, $\overline{R}_{\max}$ and T_a to indicate the maximum SMSN, the minimum SMSN and the ascending length, respectively, of a solar cycle. A combination of $\overline{R}_{\min}$, $\overline{R}_{\max}$, T_a and the feature of the SMSN time profile of a solar cycle should be able to describe the outlook of the cycle.

Our similar cycle prediction method is quite simple. It was firstly applied to the SMSN prediction of cycle 23, and then to the peak time prediction and the solar flux prediction at 2800 MHz for cycle 23. These predictions are successful[20,21]. The steps of the method include that (1) Primary selection of similar cycles: according to the predicted values $\bar{R}_{\min}$ (pred), $\bar{R}_{\max}$ (pred) and T_a (pred) of the predicted solar cycle. Those cycles whose $\bar{R}_{\min}$, $\bar{R}_{\max}$ and T_a are respectively near $\bar{R}_{\min}$ (pred), $\bar{R}_{\max}$ (pred) and T_a (pred) are selected to be the primary similar cycles; (2) Final selection of similar cycles: if there are some significant differences between the forms of the time profiles of these primary similar cycles, the cycles whose time profiles show some common characteristics are used as the final similar cycles; and (3) Predicting the SMSN: the average made of the SMSNs of these final selected similar cycles for month *i*, $\bar{A}_i$, is taken as the prediction of the SMSN for the month *i* for the predicted cycle, as shown by eq. (2). The predicted $\Delta\bar{A}_i$ is given by eq. (3):

$$\bar{A}_i = \frac{1}{N}\sum_n \bar{R}_{i,n}, \tag{2}$$

$$\Delta\bar{A}_i = \sqrt{\frac{\sum_n (\bar{R}_{i,n} - \bar{A}_i)^2}{N-1}}, \tag{3}$$

where *N* is the number of the similar cycles and *n* is the number of a similar cycle used.

The similar cycle method used here is basically facing two important problems, which are how to find a few cycles similar to the predicted cycle to a certain degree, and whether the prediction errors satisfy the needs of the users (e.g. errors ⩽ 30%). To resolve these problems, taking cycle 23 as an example, we compare the predictions for three different cases with the observed SMSNs of cycle 23. In the first case cycles 1—22 are involved, the second case consists of cycles 9—22 and the third one cycles 11—22, respectively. For each of the three cases, by using eqs. (2) and (3), we obtain three time sequences, which are $\bar{A}_i$, $\bar{A}_i + \Delta\bar{A}_i$ and $\bar{A}_i - \Delta\bar{A}_i$. Then we compare them with the observed SMSN time sequence, $\bar{R}_i$, of cycle 23. The comparisons for the three cases are given in Figures 1—3, respectively.

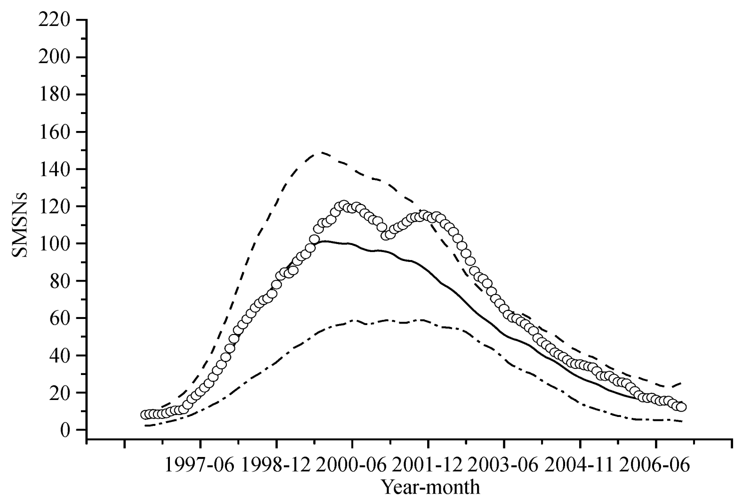

Figure 1 Comparison of the SMSN time profile made of cycles 1 to 22 for $\bar{A}_i$ (solid line), $\bar{A}_i + \Delta\bar{A}_i$ (dashed line) and $\bar{A}_i - \Delta\bar{A}_i$ (dashed and dotted line) with the observed SMSNs (circle line) of cycle 23.

Figure 2 The same as in Figure 1, except for using cycles 9 to 22.

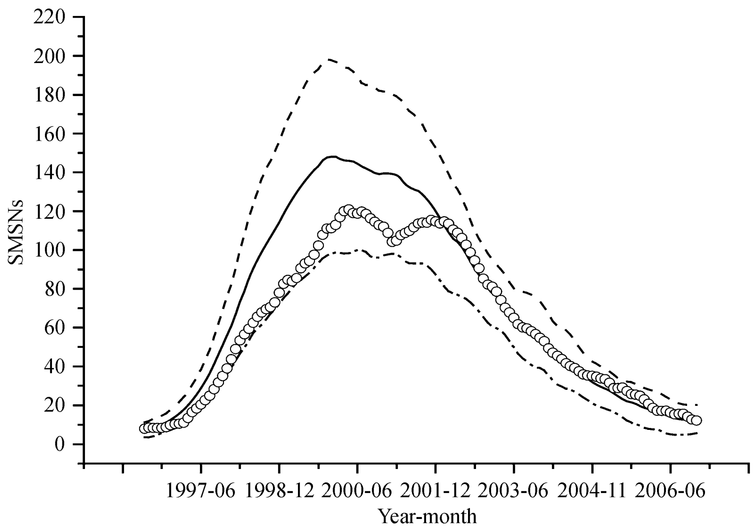

Figure 3 The same as in Figure 1, except for using cycles 11 to 22.

From Figures 1—3, we can have the following points: (1) Figure 1 shows that time profiles $\overline{A}_i$ and $\overline{R}_i$ are well consistent with each other for the ascending phase, but not for the peak and descending phases; (2) Figure 2 shows that the consistency of $\overline{A}_i$ and $\overline{R}_i$ for the ascending phase is not as good as shown in Figure 1, but the consistency is improved for the peak phase; (3) Figure 3 shows that the time profiles of $\overline{A}_i$ and $\overline{R}_i$ are consistent with each other quite well for the descending phase, but not for the other parts; (4) the relative standard errors show a gradual decrease from Figure 1 to Figure 3; (5) the maximum value of $\overline{A}_i$ changes gradually from the value lower than that of $\overline{R}_i$ to higher than that of $\overline{R}_i$, from Figure 1 to Figure 3; and (6) Figures 1—3 show an obvious change from a single peak to the double-peak like structure of the predicted profile, which is more similar to the one of the observed cycle 23. The facts mentioned above reveal that for a certain solar cycle (for example, cycle 23) it is possible to find some cycles similar to the certain one in some aspects and the $\bar{A}_i$ time profile calculated from these selected similar cycles (see eq. (2)) can be used as a predicted time profile for the certain cycle.

In the same way as discussed above, 7 solar cycles including cycles 8, 9, 11, 17, 18, 20 and 21 are selected as the similar cycles to solar cycle 23. Thus, the calculated $\bar{A}_i$ and $\Delta\bar{A}_i$ can be used as the predictions of $\bar{R}_i$ and the error for cycle 23[15], respectively. In Figure 4, the predicted SMSNs for cycle 23 are compared with the observed ones.

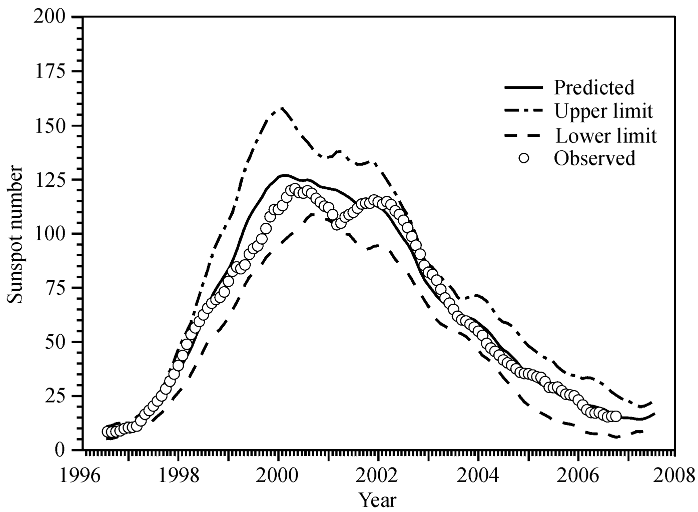

Figure 4 Comparison of $\bar{A}_i$ and $\pm\bar{A}_i$ with $\bar{R}_i$ for cycle 23.

Clearly, this is a very successful prediction and it is worth trying to apply this method to the prediction of SMSNs for cycle 24.

2 Prediction of SMSNs for solar cycle 24 by the similar cycle method

Considering the predictions of the parameters for cycle 24[14,22], we take the predicted parameters for cycle 24 to be $\bar{R}_{\min}\,(\text{pred}) = 7.0 \pm 3.6$, $\bar{R}_{\max}\,(\text{pred}) = 125 \pm 25$, and $T_a\,(\text{pred}) = 3.6 \pm 0.6$ years. Then cycles 2, 4, 8, 11, 17, 20 and 23 are selected to be the similar cycles of cycle 24. Some parameters of these 7 similar cycles and of cycle 24 are given in Table 1.

It has been known that the sunspot number records after 1849 are of more reliability[23]. We divide the seven similar cycles listed in Table 1 into two groups. The first group comprises only the

Table 1 Main parameters of solar cycle 24 and the cycles similar to cycle 24

Cycle No.	$\bar{R}_{i,\min}$	T_a (years)	$\bar{R}_{i,\max}$
2	11.2	3.2	115.8
4	9.5	3.4	141.2
8	7.3	3.3	146.9
11	5.2	3.4	140.5
17	3.4	3.6	119.2
20	9.6	4.0	110.6
23	8.0	4.0^*	120.8
24^*	$7.0^* \pm 6$	$3.6^* \pm 0.6$	$125^* \pm 25$

Remark: *—predicted.

four similar cycles, cycles 11, 17, 20 and 23, and the second group comprise all the seven similar cycles. Then, by using eq. (2) we predict the SMSNs of cycle 24 for the two similar cycle groups and show them in Figure 5, where the abscissa represents the time in months, while the ordinate the SMSN. It can be found that there is no significant difference for the two predicted curves in Figure 5.

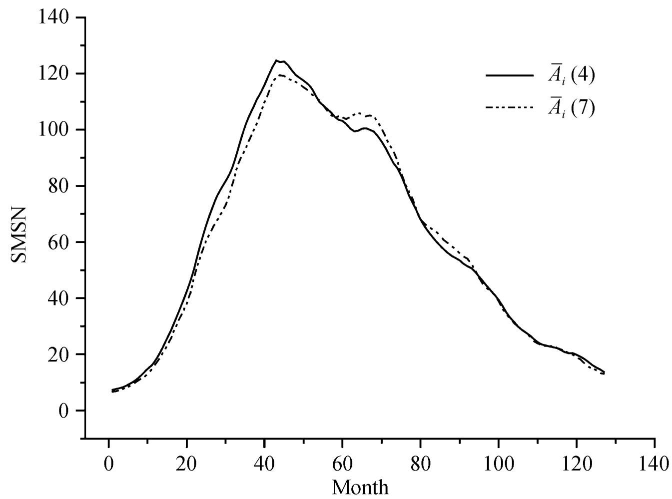

Figure 5 The predicted time profile for cycle 24 using similar cycles 11, 17, 20 and 23 ($\bar{A}_i(4)$, solid) and using similar cycles 2, 4, 8, 11, 17, 20 and 23 ($\bar{A}_i(7)$, dashed).

The final step for the present prediction is to make a date calibration for the curves in Figure 5. The following facts that (1) the start time of cycle 24 was predicted in May 2007; (2) the start time of cycle 24 was estimated by an intonation panel to be in March ± 6 months 2008 and (3) the recently observed data show that there were 21 spotless days in September 2007, 28 spotless days in October, and 24 spotless days in November are considered. Then, the date, October ± 5 months 2007, is taken as the start time of solar cycle 24. Actually, in this paper $\bar{A}_i(4) \pm \Delta\bar{A}_i(4)$ is used as the final predictions of SMSNs for cycle 24 and shown in Figure 6, as well as listed in Tables 2 and 3.

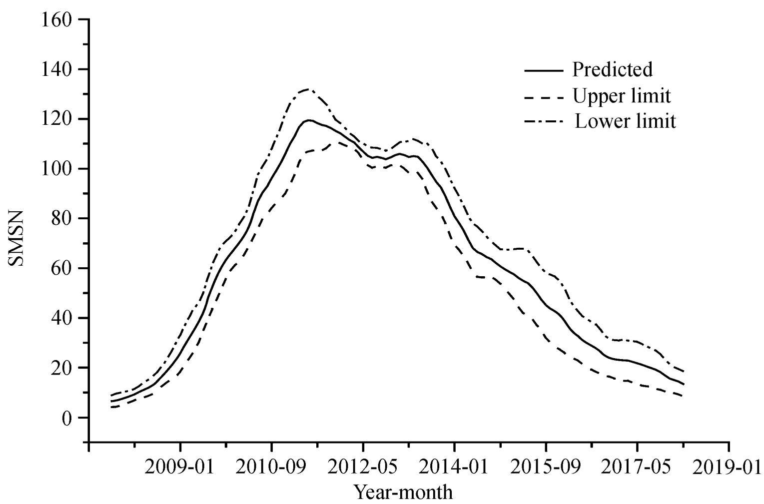

Figure 6 The predicted time profile with errors of SMSN for solar cycle 24.

Table 2 Predicted values of SMSNs for solar cycle 24 (January－June)

Year	Jan	Feb	Mar	Apr	May	Jun
2007						
2008	7.9±2.4	8.5±2.3	9.2±2.2	10.1±2.5	11.1±3	11.9±3.3
2009	25.9±7.5	29.2±7.9	32.2±8.4	35.1±8.6	38.2±7.9	42.2±7.6
2010	68.1±6.8	70.5±7.4	73.1±7.6	76.9±7.9	81.9±9.4	87±10.8
2011	109.8±16.3	113.1±15.4	116.6±14.1	118.8±12.8	119.4±12.4	119.2±11.9
2012	112.8±3.5	111.5±2.8	110.5±2.4	108.7±2.4	106.9±3.3	105.2±3.7
2013	106±4.6	105.5±5.4	104.7±6.3	105.1±6.7	104.8±6.4	102.8±7.2
2014	80.8±11.3	78±10.7	75.1±10.1	71.4±9.5	68.1±9.9	66.5±10.1
2015	58.5±9.0	57.5±10.1	56±11.8	54.9±13	54±13.0	52.3±12.7
2016	39±13.0	36.2±11.5	34.2±10.5	32.7±9.9	31.1±9.6	29.8±9.6
2017	23.0±8.0	23.0±8.3	22.8±8.1	22.3±8.4	21.8±8.7	20.1±8.4
2018	15.0±5.3	14.4±5.2	13.4±5.0	13.1±4.2		

Table 3 Predicted values of SMSNs for solar cycle 24 (July－December)

Year	Jul	Aug	Sep	Oct	Nov	Dec
2007				6.6±2.4	6.9±2.6	7.3±2.5
2008	12.9±3.5	14.6±3.6	16.5±4.0	18.5±4.5	20.8±5.5	23±6.7
2009	47.7±8.5	52.4±8.9	56.6±9.0	60.4±8.7	63.3±7.5	65.8±6.7
2010	90.4±10.7	92.9±11	96.2±12.1	99.3±12.9	102.4±14.5	106.2±16.1
2011	118.3±10.9	117.5±10.1	117.1±8.7	116.2±6.2	115.1±4.5	114.2±4
2012	104.4±4.1	104.8±3.7	104.4±3.6	103.8±3.4	104.6±3.2	105.4±3.8
2013	100.4±9.7	97.4±10.7	94.6±10.4	92.4±10.5	89±11.0	84.5±11.5
2014	65.7±9.4	64.5±8.2	63.6±7.2	62.2±6.9	60.7±7.0	59.6±7.9
2015	49.8±12.7	47.3±12.6	45±13.1	43.6±13.7	42.5±14.1	41.1±13.8
2016	28.8±9.7	27.7±9.5	26.3±8.9	24.7±8.0	23.9±7.6	23.4±7.8
2017	20.5±8.0	19.9±7.8	19.1±7.7	18.2±7.1	16.9±6.4	15.6±6.0

3 Conclusions and discussion

Predictions for SMSNs of solar cycle 24 are quite spread. For examples, Wang et al.[14] predicted the maximum SMSN to be of 125 for cycle 24, Duhau[24] predicted the maximum to be 87, Li et al.[25] predicted that the peak of cycle 24 would be 189.9 or 136 and 137 or 80, Du & Du[26] gave the prediction of 114.8, Du[27] gave the prediction of 150.3, etc. The international panel (see http://www.sec.noaa.gov/solar cycle/sc24/statemetn_01.html) estimated that cycle 24 would start in March ± 6 months 2008 and supported 140 ± 20 or 90 ± 10 for the $\bar{R}_{max}$ of cycle 24. Furthermore, Li et al.[28] carefully compared the predictions produced by various methods and discussed a prediction obtained from a combination of several methods. Recently the evolution of the sunspot activity level in the descending phase of solar cycle was studied, and the road along which the level evolves was given[29]. Kane[30] listed 43 predictions of the peak SMSN for cycle 24, which cover a broad range from 50 to 200. It seems to be very necessary to develop an applicable and reasonably good method for predicting the SMSNs of the next cycle. The following results may be deduced from our work:

(1) 127 SMSNs are predicted for cycle 24 in this paper. The prediction covering most parts of cycle 24 from its beginning on is produced simultaneously, with an average time length of about 5 years in advance, by our similar cycle method. The prediction made by using this method does not have the error integration problem, and so, its errors do not increase with time in advance. The error

depends on the conditions for selecting similar cycles and the number of the similar cycles. This kind of study may be of some significance in developing an effective method for solar activity prediction of all the individual months of a cycle, and hence for the space weather.

(2) Both curves given in Figure 5 show that cycle 24 will have a broad peak phase, even a second peak should appear in the first half of the descending phase of cycle 24.

(3) This work predicts that solar cycle 24 will have its maximum SMSN of 119.5 ± 12.4, and its ascending length of 44±5 months, and begin in the range from May 2007 to March 2008. The date calibration is an important step in this prediction, and should affect the accuracy of the phase prediction to some extent.

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