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A preliminary estimate of the size of the coming Solar Cycle 23, based on Ohl's precursor method

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Abstract. Solar Cycle 22 seems to be nearing its end. The 12-month moving averages of sunspot number and aa index seem to have levelled near 8.1 and 17.9. If these are confirmed as the minimum values, a prediction for Cycle 23 by the precursor method indicates a maximum amplitude of 170 ± 13 (by the single variable regression analysis) and 177 ± 21 (by the bivariate analysis), suggesting that cycle 23, potentially, will be one of the largest sunspot cycles on record (i.e., Rmax > 160).

Introduction

The size of a sunspot cycle is very crucial for a variety of physical effects on the Earth or in its vicinity, as also for various technologies such as operation of low-Earth orbiting satellites, electric power transmission grids, geophysical exploration, high-frequency radio communications and radars. Hence, accurate prediction of its size several years ahead has been an important goal for solar forecasters. A wide variety of methods have been used; e.g., predictions based on even/odd behaviour of sunspot numbers, precursor techniques, spectral analysis, neural networks and climatology. A review of the observed and expected values of maximum sunspot number for Cycle 22 was given by Kane [1992]. For solar Cycle 23, predictions have been given by Kopecky [1991], Wilson [1992], Schatten and Pesnell [1993], Schatten et al. [1996] and many others. The NOAA Space Environment Center (SEC), with the support of NASA Office of Space Science, recruited a scientific panel to assess the likely development of Cycle 23. Their report entitled "Solar Cycle 23 Project: Summary of Panel Findings" by Joselyn et al. (to appear later as a NOAA Technical Memorandum), hereafter referred to as JOETAL, mentions a range 165-200 for maximum sunspot number for Cycle 23, as obtained by considering the even/odd behaviour, and a range of 110-160 by other methods.

Amongst the various methods used for prediction of solar activity, the "precursor" methods are considered the most successful. Initiated by Ohl [1966] and Brown and Williams [1969], these methods indicated that geomagnetic activity in the declining phase of a sunspot cycle could be useful for the prediction of the solar activity in the next cycle. This was puzzling, as the solar activity is the cause of geomagnetic activity and hence the former must precede the latter. A plausible explanation was offered by Schatten et al. [1978], based on the "solar dynamo" theory, wherein the polar field serves as a seed for future solar activity. Schatten and Pesnell [1993] developed a Solar Dynamo Amplitude (SODA) index, describing the amount of the buoyant solar magnetic field flux, and used this index to predict a sunspot number of 170 ± 25 for Cycle 23. Thompson [1993] described a precursor technique where the numbers of geomagnetic disturbances during a solar cycle were correlated with the amplitudes of the current cycle as well as the amplitudes of the next cycle and used the technique to predict the amplitude of Cycle 22 fairly accurately (predicted 148.3; observed 158.5). Using geomagnetic indices and sunspot numbers at the solar minimum in single variable and bivariate analyses, several workers gave forecasts for the maximum sunspot numbers in Cycles 20, 21, 22 [e.g., Ohl, 1966, 1976; Ohl and Ohl, 1979; Sargent, 1978; Kane, 1978, 1987; Wilson, 1988a, 1990]. In recent months, the solar activity has been declining. In this paper, we examine whether the end of Cycle 22 has occurred and, if so, whether a preliminary prediction for the amplitude of Cycle 23 could be hazarded.

Data

The data used are the geomagnetic aa indices (the antipodal amplitudes deduced from the K index of Greenwich, England and Melbourne, Australia) and sunspot numbers [Mayaud, 1973; McKinnon, 1987 and further data from Solar-Geophysical Data]. Table 1 gives the monthly (mon) values, the 12-month (12) moving averages and the annual (anu) values for aa and sunspot numbers and their months of occurrence, for the past solar cycles. For aa, data are available from 1868 only (Cycle 11). However, for 1844-1880, Nevanlinna and Kataja [1993] generated an "equivalent" aa index based on the declination data from Helsinki and, for the overlapping period of 13 years 1868-1880, they found a very high correlation (0.99). In Table 1, the annual values for aa(min) for Cycles 9, 10, 11 are based on the Helsinki equivalents and have ± 1.8 units of 95% confidence level.

Correlation analysis and regressions

A correlation analysis between the parameters of Table 1 showed that some correlations were very high (exceeding 0.9). In particular, the high correlations of R(max)12 and R(max)anu with aa(min)12 and aa(min)anu indicated the strong possibility of R(max) prediction, given either aa(min)12 or aa(min)ann. The correlations of R(min)12 and R(min)anu with R(max)12 and R(max)anu were low (~0.5). But a bivariate analysis correlating R(max) with aa(min) and R(min) gave high positive partial correlations between R(max) and aa(min) and high negative partial correlations between R(max) and R(min). For 12-month moving averages, a regression analysis using data for Cycles 12-22 gave the following regression equations:

$$\text{Corr. } 0.91,\ R(max) = (5.9 \pm 18.3) + (9.2 \pm 1.4)aa(min) \qquad (1)$$

$$\text{Corr. } 0.95,\ R(max) = -(3.5 \pm 15.1) + (12.1 \pm 1.6)aa(min) - (4.4 \pm 1.8)R(min) \qquad (2)$$

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Table 1. Values of aa(min), R(min) and R(max) for Cycles 9-22; monthly means (mon), 12-month moving averages (12), annual averages (anu).

Cycle	aa(min) (mon)	aa(min) (12)	aa(min) (anu)	R(min) (mon)	R(min) (12)	R(min) (anu)	R(max) (mon)	R(max) (12)	R(max) (anu)
9	x	x	14.0	3.7	10.5	10.7	180.4	131.6	124.7
			1845	6-1864	7-1843	1843	10-1847	2-1848	1848
10	x	x	10.3	0.0	3.2	4.3	116.7	97.9	95.8
			1856	9-1855	12-1855	1856	7-1860	2-1860	1860
11	x	x	16.0	0.0	5.2	7.3	176.0	140.5	139.0
			1867	1-1867	3-1867	1867	5-1870	8-1870	1870
12	4.7	6.8	7.0	0.0	2.2	3.4	95.8	74.6	63.7
	2-1880	1-1879	1879	8-1878	12-1878	1878	4-1887	12-1883	1883
13	7.3	10.7	10.7	0.2	5.0	6.3	129.2	87.9	85.1
	6-1890	7-1890	1890	11-1889	2-1890	1889	8-1893	1-1896	1893
14	4.7	6.0	6.1	0.0	2.6	2.7	108.2	64.2	63.5
	6-1900	12-1900	1901	4-1901	1-1902	1901	2-1907	2-1906	1905
15	6.6	8.2	8.7	0.0	1.5	1.4	154.5	105.4	103.9
	12-1913	9-1913	1913	2-1912	7-1913	1913	8-1917	8-1917	1917
16	6.9	9.4	10.2	0.5	5.6	5.8	108.0	78.1	77.8
	8-1924	10-1924	1924	8-1923	7-1923	1923	12-1929	4-1928	1928
17	9.5	13.3	13.4	0.2	3.4	5.7	165.3	119.2	114.4
	11-1934	6-1934	1934	8-1933	9-1933	1933	7-1938	4-1937	1937
18	11.1	16.4	16.4	0.3	7.7	9.6	201.3	151.8	151.6
	7-1944	4-1945	1945	4-1944	2-1944	1944	5-1947	5-1947	1947
19	9.7	17.0	17.3	0.2	3.4	4.4	253.8	201.3	190.2
	6-1954	4-1955	1954	1-1954	4-1954	1954	10-1957	3-1958	1957
20	10.3	13.9	14.1	3.1	9.6	10.2	135.8	110.6	105.9
	12-1964	5-1965	1965	7-1984	10-1964	1964	3-1969	11-1968	1968
21	12.7	17.0	18.1	4.3	12.2	12.6	188.4	164.5	155.4
	3-1980	4-1980	1980	2-1976	3-1976	1976	9-1979	12-1979	1979
22	12.9	17.5	19.0	1.1	12.3	13.4	200.3	158.5	157.6
	4-1987	12-1986	1987	6-1986	9-1986	1986	8-1990	7-1989	1989

For the annual values, regression equations using Cycles 9-22 were as follows:

$$\text{Corr. } 0.92,\ R(max) = (6.4 \pm 14.1)+(8.5 \pm 1.0)aa(min) \quad (3)$$

$$\text{Corr. } 0.97,\ R(max) = -(4.6 \pm 9.6)+(12.1 \pm 1.1)aa(min) - (5.1 \pm 1.2)R(min) \quad (4)$$

R and aa near the end of cycle 22: Prediction for cycle 23

Wilson et al. [1996] examined the behaviour of the sunspot cycle near minimum for Cycles 12-21 and indicated that Cycle 22 is probably a short-period cycle. Considering the decline of Cycle 22 in terms of sunspot number, the number of spot groups, and the weighted mean latitude, they surmised that Cycle 23 onset may occur on or about December 1996 (±3 months). We now examine the behaviour of 12-month moving averages of aa index and sunspot number (R).

Figure 1 shows a plot of the 12-month (double-smoothed) moving averages of sunspot number (R) (full lines, with markings for December) and aa indices (dots), for solar Cycles 12-22. The vertical line marks R(min). The following may be noted:

a) The 12-month moving averages of sunspot number R (full lines) decrease monotonically to a minimum, remain at or very near the minimum level for a few months and commence a rise. Thus, once the values reach a low level and remain there for a few months, this level is the R(min), not likely to be lowered in the next few months.

b) The 12-month moving averages of the aa index seem to attain aa(min) (values indicated) 0 to 15 months past R(min) (lags indicated by circled numbers). Two glaring exceptions were, Cycle 14 when aa(min) occurred before the R(min) and, Cycle 21 when aa showed a first minimum 6 months after the R(min), rose thereafter, but showed a lower minimum again, several years later.

c) For Cycles 12, 13, 15, 17, 18, 19, 20 and 21, the aa values at R(min) were still declining and obviously, aa(min) was still far away. In Cycle 14, aa(min) had occurred before R(min). In Cycles 16 and 22, aa values had levelled at R(min); however, in Cycle 16, the aa values remained near this steady level for almost a year and then showed further decrease. In contrast, in Cycle 22, the steady level of aa at R(min) was maintained and was the aa(min). Thus, a steady level of aa at R(min) may or may not be the aa(min).

Let us examine now the behaviour of R and aa in recent months. Fig. 1, right half, bottom panel shows the monthly means and the 12-month moving averages (superposed) of the sunspot numbers R and the aa indices. The monthly values vary considerably and the trend is not obvious. In the 12-month moving averages, the R values from January to October 1996 are 10.4, 10.2, 9.7, 8.5, 8.1, 8.6, 8.5, 8.5, 8.6, 8.9, thus indicating a minimum value of 8.1 in May 1996. From our experience of the previous cycles, this value (or values very near the same) will probably be the R(min). In the plot for aa, the 12-month moving averages centered from January to October 1996 are 18.7, 18.8, 19.0, 19.0, 18.8, 18.7, 18.5, 18.5, 18.2, 17.9. Thus, an almost steady level is seen. If this behaviour mimics that of Cycle 22, aa(min) should be about 17.9. However, if the behaviour resembles that of Cycle 16, a further drop may occur within the next few months; or, if the behaviour resembles that of Cycle 21, aa(min) could occur much later, losing all its prediction potential. Using the values aa(min) = 17.9 and R(min) = 8.1, the provisional

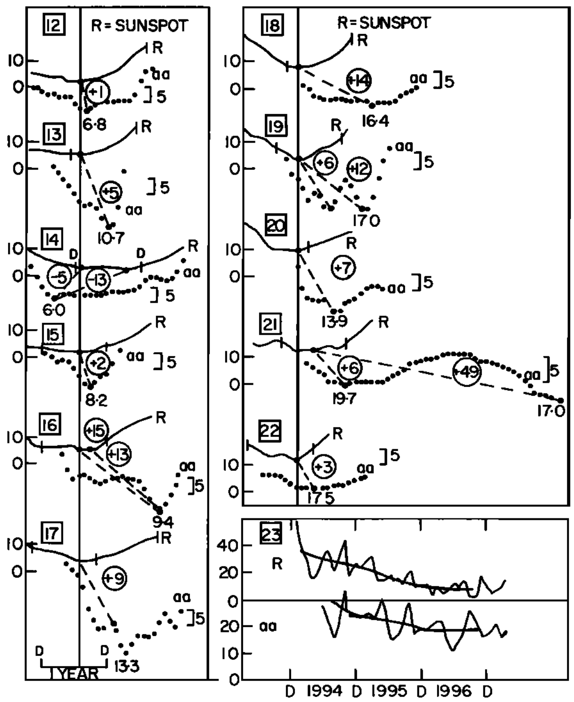

Figure 1. Plots of the 12-month moving averages of the sunspot number (full lines, with small markings indicating December and the main vertical line indicating sunspot minima) and the aa index (dots) for Cycles 12-22. The aa minima (values indicated) are connected to the sunspot minima by dashed lines and the lag in months is indicated by circled numbers. The bottom plot of the right half shows the monthly values and the 12-month moving averages (superposed) of sunspot number and aa indices for Cycle 22-23 (1994-1997).

predictions for R(max) are 170 ± 13 from the single variable analysis (equation (1)) and, 177 ± 21 from the bivariate analysis (equation (2)). Since the annual values for 1996 for aa and R are 18.7 and 8.7, and these are likely to be the lowest, the predictions for R(max) are 163 ± 13 from the single variable analysis (equation (3)) and 175 ± 21 from the bivariate analysis (equation (4)).

Other predictions for cycle 23

A. Precursor Methods

Since Schatten et al. [1978] offered a plausible explanation for the basis of the precursor methods, their group has been predicting solar activity amplitudes for future cycles. For Cycle 23, Schatten and Pesnell [1993] used the SODA index then available and made an early estimate of sunspot number of 170 ± 25 but commented that the peak of Cycle 23 may exceed this early estimate, as the Sun's polar field may increase when solar minimum is reached. However, in a more recent paper, Schatten et al. [1996] use the SODA index and predict a much lower value (viz. 138 ± 30), leaving in some doubt the reliability of this method. Thompson [1993] correlated the number of geomagnetic disturbances in a cycle with the amplitudes of that and the next cycle and predicted the amplitude of Cycle 22 fairly accurately (predicted 148.3; observed 158.5). For Cycle 23, Thompson [1996, and further private communication] mentions 164, based on Ap values up to May 1996. Using Ap values in a slightly different way, Li [1997] predicted 149 ± 20. We attempted a simpler version of this technique by counting the number of months when the monthly aa index exceeded 15, 20 and 25. Data for 1996 are not yet fully available; but the contribution from the last few months of 1996 for these aa limits is expected to be very small and hence, predictions can be hazarded. Using data for earlier cycles, the regression equations obtained were as follows:

Thompson [1993], Corr. 0.97, $Nc = -(47.7 \pm 45.8)$

$$+ (2.20 \pm 0.33)\,Rc + (1.88 \pm 0.32)\,Rn \quad (5)$$

Our aa >15, Corr. 0.89, $Nc = (10.1 \pm 14.8)$

$$+ (0.30 \pm 0.11)\,Rc + (0.35 \pm 0.10)\,Rn \quad (6)$$

Our aa >20, Corr. 0.94, $Nc = -(31.2 \pm 11.2)$

$$+ (0.41 \pm 0.08)\,Rc + (0.30 \pm 0.08)\,Rn \quad (7)$$

Our aa >25, Corr. 0.95, $Nc = -(28.4 \pm 6.5)$

$$+ (0.27 \pm 0.05)\,Rc + (0.17 \pm 0.05)\,Rn \quad (8)$$

where Nc is the number of disturbances in Thompson [1993] and in our case, aa exceeding 15, 20, 25, Rc is the amplitude of sunspot numbers in the current cycle, and Rn is the sunspot amplitude in the next cycle. Using the values of the numbers of aa exceeding 15, 20 and 25 during Cycle 22 up to October 1996, the predicted values of Rn (sunspot amplitude for Cycle 23) were, respectively, 147, 191 and 227. Which one of these is the most reliable, however, is difficult to judge. In JOETAL, the precursor method prediction range is reported as 140 (low end) to 180 (high end).

B. Other Methods

Wilson [1992] gave predictions for RM (the maximum value of smoothed sunspot number) for Cycle 23 by different methods viz.

135.5 ± 41.5, as a mean of odd-numbered cycles,
198.8 ± 14.2, basis, the mean "difference" and known value of RM for Cycle 22 (158.5),
164.1 ± 34.2, from the inferred upward trend in RM,
213.9 ± 13.5, from the RM(odd) versus RM(even) fit.

Using information available upto 1992, Obridko et al. [1994] compiled the forecasts for the height of Cycle 23 and divided these into two main groups: (i) those based on internal regularities in a pair of cycles (e.g., the 22-year cyclicity), and (ii) those also using the secular cycle and the Wolf number variations for many years. The forecasts were:

Type (i)

- 175 ± 40, Wilson [1988b], basis, bimodality of the Hale cycle, using RM and aa index.
- 208.3, Kopecky [1991], basis, alternating heights of the 11-year cycles in even-odd pairs.
- 225 ± 8, Rivin [1992], basis, the smoothed secular variation of the ratio of heights of the odd and the even cycles in the pair.
- 140 ± 10, Tritakis [1986], basis, the relation between the steepness of the growth and the decay branches and the heights of the cycles in a pair.
- > 160, Makarov and Mikhailutsa [1991], basis, the dynamics of large-scale magnetic fields.

Type (ii)

85-120, Schove [1983], basis, secular, 200-year and longer variations of the Wolf sunspot number.

75, Chistyakov [1983], basis, secular variations and relation of 3 successive 11-year cycles.

110, Kontor et al. [1983], basis, two envelopes of the Wolf numbers for many years.

As observed by Obridko et al. [1994], the forecasts include extremely high, moderate and low values, the high values being in group (i) and moderate and low values in group (ii).

Conclusions and discussion

Solar Cycle 22 seems to be nearing its end. The 12-month moving averages of sunspot number have levelled near 8.1 and those of aa index near 17.9. If these values are, indeed, the minimum values for Cycle 23, then predictions of the maximum amplitude of Cycle 23 are, 170 ± 13 (from the single variable analysis) and 177 ± 21 (from the bivariate analysis). For Cycle 22, the single variate method gave 165 ± 35 for the maximum amplitude, while the bivariate method gave 145 ± 15; the observed value measured 159.

In conclusion, the range of predictions for the maximum amplitude of Cycle 23 that has been reported by several workers is very wide. A similar situation occurred for Cycles 21 and 22. For Cycles 9-22, 6 cycles had maximum amplitudes between 64 and 109, 5 had maximum amplitudes between 110 and 155 and 3 had maximum amplitudes between 156 and 201. Thus, our prediction of ~175 for Cycle 23 is within the high maximum amplitude range, much larger than that recently predicted by Schatten et al. [1996] (i.e., 138 ± 30).

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