DID PREDICTIONS OF THE MAXIMUM SUNSPOT NUMBER FOR SOLAR CYCLE 23 COME TRUE?

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Abstract. For solar cycle 23, the maximum sunspot number was predicted by several workers, and the range was very wide, ~80–210. Cycle 23 started in 1996 and seems to have peaked in 2000, with a smoothed sunspot number maximum of ~122. From about 20 predictions, 8 were within 122 ± 20. There is an indication that a long-term oscillation of ~80–100 years may be operative and might have peaked near cycle 20 (1970), and sunspot maxima in cycles in the near future may be smaller and smaller for the next 50 years or so and rebound thereafter in the next 50 years or so.

1. Introduction

The size of a sunspot cycle is crucial for many terrestrial effects such as operation of low-Earth orbiting satellites, electric power transmission grids, geophysical exploration, high-frequency radio communications and radars, etc. Soon after the IGY (1957–1958) when solar activity reached a level higher than anything reached before, efforts were started to predict solar activity. A wide variety of methods have been proposed; e.g., predictions based on even/odd behavior of sunspot numbers, precursor techniques, extrapolation of spectral components, neural networks and climatology. Some of these, notably the precursor methods (Ohl, 1966; Brown and Williams, 1969, where the precursor is the geomagnetic activity in the declining phase of the previous cycle) made reasonably good predictions for solar cycles 20 (1964–1975), 21 (1976–1985), and 22 (1986–1995) (Ohl, 1966, 1976; Ohl and Ohl, 1979; Sargent, 1978; Kane, 1978, 1987; Wilson, 1988a, 1990). A review of the observed and predicted values of the maximum sunspot number for cycle 22 was made by Kane (1992). For solar cycle 23, many predictions were made. Cycle 23 started in 1996 and seems to have already peaked in 2000, with a maximum smoothed sunspot number of ~122. In this communication, the predictions for cycle 23 are reviewed to see which ones proved to be reasonably accurate.

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2. Predictions

For cycle 23, early predictions were by Kopecký (1991), Wilson (1992), Schatten and Pesnell (1993), Schatten, Meyers, and Sofia (1996), and many others. Wilson (1992) gave predictions of R(max) (the maximum value of smoothed Wolf or Zürich sunspot number Rz) for cycle 23 by different methods. Those predictions varied widely as: (i) 136 ± 42, as a mean of odd-numbered cycles, (ii) 199 ± 14, based on mean 'difference' and known value of RM for cycle 22, (iii) 164 ± 34, from the inferred upward trend in sunspot maxima, and (iv) 214 ± 14, from the R(max)(odd) versus R(max)(even) fit. Using information available up to 1992, Obridko, Oraevsky, and Allen (1994) compiled the forecasts 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), based on bimodality of the Hale cycle (22 years), using R(Max) and aa index.
208, Kopecký (1991), based on alternating heights of the 11-year cycles in even/odd pairs.
225 ± 8, Rivin (1992), based on the smoothed secular variation of the ratio of heights of the odd and the even cycles in the pair.
140 ± 10, Tritakis (1986), based on the relationship between the steepness of the growth and the decay branches and the heights of the cycles in a pair.
>160, Makarov and Mikhailutsa (1991), based on the dynamics of large-scale magnetic fields.

Type (ii)

85–120 Schove (1983), based on secular, 200-year and longer variations of the Wolf sunspot number Rz.
75 Chistyakov (1983), based on secular variations and relation of 3 successive 11-year cycles.
110 Kontor *et al.* (1983), based on two envelopes of the Wolf numbers Rz for many years.

Thus, as observed by Obridko, Oraevsky, and Allen (1994), group (i) had high values and group (ii) had moderate and low values. Soon after, 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 (1996 onwards). Their report entitled 'Solar Cycle 23 Project: Summary of Panel Findings', later published as Joselyn *et al.* (1997), mentioned (i) a range 160–200 of R(max) of cycle 23 as obtained by considering the even/odd behavior, and (ii) a range 110 – 160 of R(max) by other methods. During the last decade, many other predictions have been made based on:

(i) GM, geomagnetic field;

(ii) SM, solar magnetic field, coronal holes etc.;

(iii) T, time series studies (TN, neural network);

(iv) OM, other and/or mixed methods.

These are Schatten and Pesnell (1993) (SM, 170), Letfus (1994) (GM, 181), Calvo, Ceccatto, and Piancentini (1995) (TM, 167), Jain (1997) (GM, 166), Thompson (1996) (GM, 164), Bravo and Stewart (1997) (SM, 150-190), Bounar, Cliver, and Boriakoff (1997) (GM, 158), Li (1997) (GM, 149) and Shastri (1998) (GM, 152). All these gave estimates of Rz(max) of about 150 or more. Schatten, Meyers, and Sofia (1996) gave a revised estimate (SM, 138 $\pm$ 30). After the diverse early estimates of Wilson (1992) mentioned earlier, a revised estimate (OM, 171 $\pm$ 18) was given by Wilson, Hathaway, and Reichmann (1998a). Later, Wilson, Hathaway, and Reichmann (1998b) reexamined the predictive aspects, using data from cycle onset to 48 months into the cycle. For cycle 23, they found that there could be two different official onsets, namely, May 1996, or August 1996. Using May 1996, they estimated the sunspot maximum number as (OM, 110.3 $\pm$ 33.1), about the size of the mean cycle, while using August 1996, their estimate was (OM, 133.3 $\pm$ 40.0), thus indicating a divergence in prediction strictly relating to the choice of the onset date. However, they indicated a preference for an estimated value exceeding 137.2. Using SSA (Single Spectrum Analysis), Rangarajan (1998) predicted (T, $\sim$ 130) and using MESA/MRA (Maximum Entropy Spectral Analysis, combined with Multiple Regression Analysis), Kane (1999) predicted (T, $\sim$ 140). Using the idea of a three-cycle periodicity (for every 3rd cycle, the aa(min) is lowest), Ahluwalia (1998) predicted (GM, $\sim$120). Hathaway, Wilson, and Reichmann (1999) gave a synthesis of solar cycle prediction techniques currently in use and gave an estimate of (OM, 154 $\pm$ 21) for a combined precursor method, and (OM, 146 $\pm$ 20) for a Combined Solar Cycle Activity Forecast as of January 1999. Using 'combined methods', Hanslmeier, Denkmayer, and Hathaway (1999) mention an estimate of (OM, $\sim$160) and Guiquing and Huaning (1999) mention an 'average' cycle. Lantos (2000) mentions that the prediction by the McNish and Lincoln Method of Boulder Prediction Center, Colorado was (OM, 133), and those by two neural networks were (TN, $\sim$122) (CNET method), and (TN, 112) (Meudon Observatory method). Thus, whereas some of the predictions are well above 150, some are below 150, nearer to the actually observed value $\sim$122.

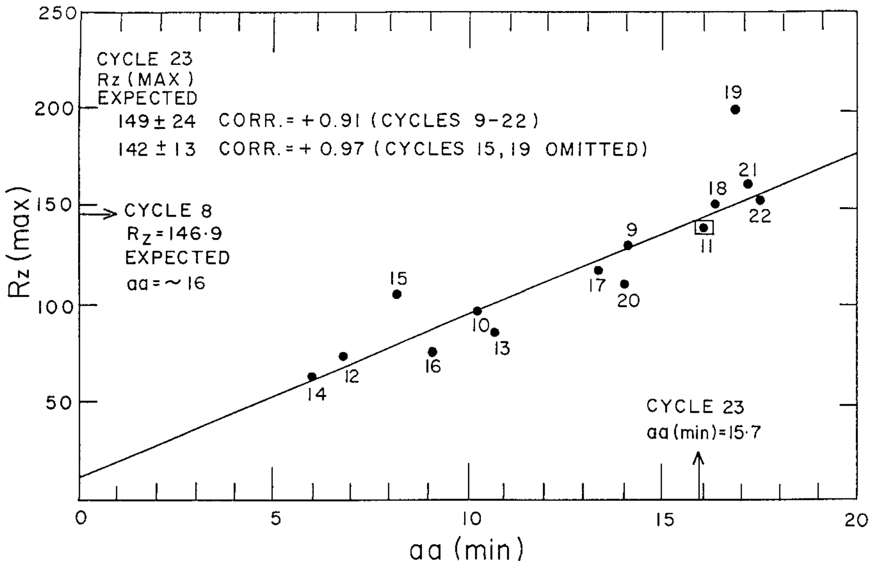

Figure 1. Plot of 12-monthly running means of *aa*(min) versus smoothed sunspot number maximum *Rz*(max), for sunspot cycles 9–22.

3. Ohl's Precursor Method

Among the various methods of prediction, Ohl's precursor method seems to yield consistently more accurate predictions. Ohl (1966) noticed that the geomagnetic activity level during the declining phase of a solar cycle was related to the maximum level of solar activity of the next cycle. Ohl (1976) used the geomagnetic activity level of cycle 20 declining phase and predicted a *R*(max) of 140–180 for cycle 21 (observed value 155). Sargent (1978) used the mean aa index for the 36 months preceding the solar minimum of 1976 and, in conjunction with the *Rz*(min) in a bivariate regression analysis, predicted *Rz*(max) as 150 or more. Even today, some workers use the activity level preceding solar minimum (Thompson, 1993, used the number of solar disturbances; Schatten and Pesnell, 1993 used SODA index, a measure of the amount of the buoyant solar magnetic field). Kane (1978) started using the annual mean geomagnetic activity aa index in the sunspot minimum year, but soon realized that the more appropriate parameter would be the 12-month moving average of aa index. Figure 1 shows the latest version of this methodology. The *Rz*(max) and *aa*(min) values are 12-month moving (running) averages and are not necessarily centered at June end, as the annual values would be. For *aa*(min), the aa data used are from Mayaud (1976) (updated from *Solar Geophysical Data* Reports) for 1868 onwards (cycle 12 onwards), but some indirect estimates of aa index were obtained from Nevanlinna and Kataja (1993) and their values for 1844–1880 could be used for cycles 9, 10, 11 (annual values only). In Figure 1, the points for cycles 9, 10, 11 lie very near the

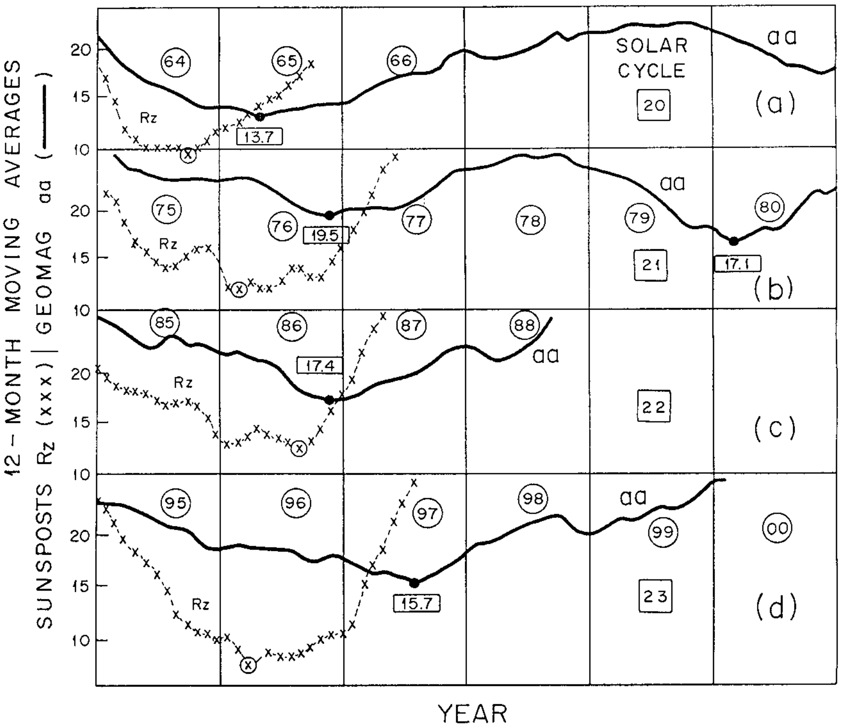

Figure 2. Plots of 12-month moving (running) averages of sunspot numbers *Rz* (*crosses*) and geomagnetic aa indices (*full lines*) for (a) solar cycle 20, 1964 onwards, (b) cycle 21, 1975 onwards, (c) cycle 22, 1985 onwards, and (d) cycle 23, 1995 onwards.

regression line, indicating that the aa estimates from Nevalinna and Kataja (1993) are reliable (for the common period 1868–1880, their correlation with Mayaud values was high, +0.96, and the values differed by less than 1.5 units). Using data for cycles 9–12, the correlation is excellent (+0.91) and the regression equation is $Rz(\max) = (8.29 \pm 15.35) + (8.96 \pm 1.17) * aa(\min)$. From these, using $aa(\min) = 15.7$ which was centered on August 1997 (later than the sunspot minimum, which occurred in April 1996), the estimate for Rz(max) of cycle 23 is 149 ± 24. In Figure 1, cycles 15 and 19 seem to deviate considerably from the regression line. If these two points are omitted, the correlation improves to +0.97, the regression equation is $Rz(\max) = (8.49 \pm 8.28) + (8.50 \pm 0.63) * aa(\min)$, and the estimate for cycle 23 becomes more accurate (142 ± 13). Table I lists the relevant values for cycles 1–22, more completely for cycle 9 onwards.

This methodology had an embarrassing problem, which is illustrated in Figure 2. To obtain the relevant value of *aa*(min) at the beginning of every cycle, the 12-month moving averages of the monthly aa values are continuously monitored. For cycles 12–20, the aa moving averages decreased monotonically until the trend reversed (few months after the sunspot minimum) and values started increasing. The lowest aa value was then the $aa(\min) = 13.7$ for cycle 20 (Fig-

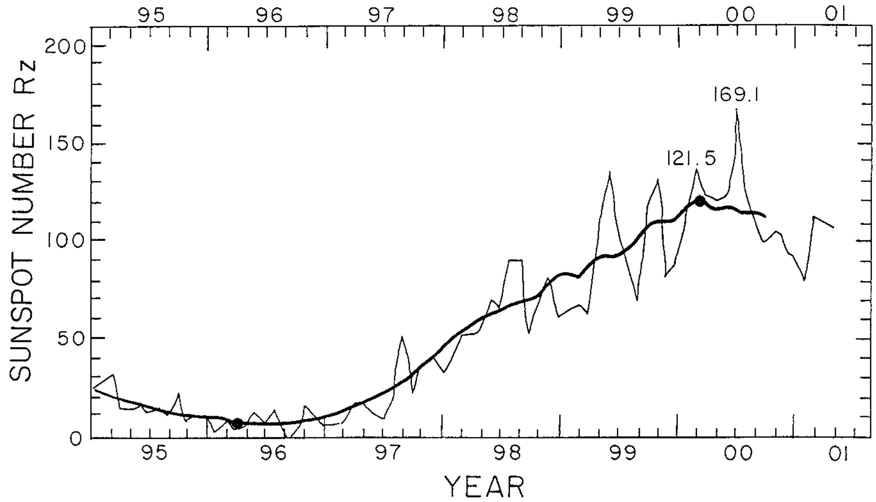

Figure 3. Plot of the Wolf sunspot number monthly values (*thin line*) and 12-month moving average (*thick line*) for solar cycle 23 (1995 onwards).

ure 2(a)). However, in cycle 21 (Figure 2(b)), the *aa*(min) showed strange behavior. An *aa*(min) = 19.5 occurred at the end of 1976 and *aa* values increased thereafter. But four years later, at the beginning of 1980, a second minimum occurred, *aa*(min) = 17.1, lower than the 1976 minimum. In Figure 1, the latter value is used for cycle 21 and fits well near the regression line. However, a prediction based on the same would have virtually no prediction potential, as it occurred very late, almost near the sunspot maximum of cycle 21. In cycles 22 (Figure 2(c)) and 23 (Figure 2(d)), such a discrepancy did not occur, but in the future, the possibility of such a hazard needs to be kept in mind. In the past, a lot of confusion occurred, resulting in premature and erroneous predictions (Kane, 1987, 1997a, 1998). Such hazards seem to occur in other methods too. Schatten and Pesnell (1993) used the SODA index available till then and predicted a sunspot maximum value of 170 ± 25. However, further data analysed by Schatten, Meyers, and Sofia (1996) indicated a much lower prediction, 138 ± 30. Similarly, until recently, Wilson, Hathaway, and Reichmann (1998a) mentioned that cycle 23 is destined to be a larger than average size cycle, commensurate with the largest cycles of modern era (i.e., cycles 18, 19, 21, 22), and that it consequently should be a fast rising cycle, peaking probably in late 1999 to early 2000. However, their further predictions (Wilson, Hathaway, and Reichmann, 1998b) using data from the cycle 23 onset in 1996 to 48 months into the cycle are of much lower values, 110–130.

4. Evolution of Sunspot Cycle 23

Figure 3 shows a plot of the monthly values (thin line) and the 12-month moving averages of the Wolf sunspot number *Rz* for 1995 onwards up to date. After reaching a value of 169.1 in July 2000, the monthly values have been on the decline. The 12-month moving average was 121.5 centered near March 2000 and is on a decline. The cycle has already completed more than four years and it seems unlikely that there will be an upturn in the sunspot number. The data for smoothed sunspot number maxima as given in McKinnon (1987) for cycles 1–20 are grouped as follows:
(a) Very low: 48.7 (6), 49.2 (5), 64.2 (14), 71.7 (7): mean value 58.5.
(b) Low: 74.6 (12), 78.1 (16), 86.5 (1), 87.9 (13):): mean value 81.8.
(c) Medium: 97.9 (10), 105.4 (15), 110.6 (2), 115.8 (2)): mean value 107.4.
(d) High: 119.2 (17), 131.6 (9), 140.5 (11), 141.2 (4)): mean value 133.1.
(e) Very high: 146.9 (8), 151.8 (18), 158.5 (3), 201.3 (19),): mean value 164.6.

The values for cycles 21 (165) and 22 (159) would rank as very high and cycle 23 (122) would rank as slightly above medium, touching high. Allowing for an (arbitrary) range of ± 20 around 122, the predictions in the range 102–142 were those of Schove (1983), Kontor *et al.* (1983), Schatten, Meyers, and Sofia (1996), Wilson, Hathaway, Reichmann (1998b), Rangarajan (1998), Ahluwalia (1998), Kane (1999), and Lantos (2000).

5. Long-Term Trend

Even though the observed value 122 is within the statistical error range of many predictions, the low value is disconcerting, as there would be nine cycles (3, 4, 8, 9, 11, 18, 19, 21, 22) having values exceeding 122. Could this be an indicator of a declining tendency? Figure 4 shows a plot of *Rz*(max) for cycles (-9 to $+22$), (a) individual values (one value for each cycle), (b) 3-cycle running averages, (c) 5-cycle running averages. In (a), no clear periodicity is visible, but in (b) there appear two swings of $\sim$ 66 and $\sim$100 years, the average of these two being $\sim$83 years, reminiscent of the Gleissberg (1965) cycle of $\sim$80 years. In (c), these appear as $\sim$ 90 and $\sim$110 years. Sunspot data series of 2–3 centuries length may not be adequate to ascertain these numbers with much confidence, and an uncertainty about their reality remains. But if these do represent genuine waves and do persist in the near future, there might have occurred a peaking around cycle 20 and the implication would be of smaller cycles in the near future. In the spectral analysis described in Kane (1999), the prediction for cycle 24 was of $\sim$105, again indicating a probable down trend.

Recently, Hoyt and Schatten (1998) re-examined all the historical records of sunspot measurements, identified new observations, derived a new and more homo-

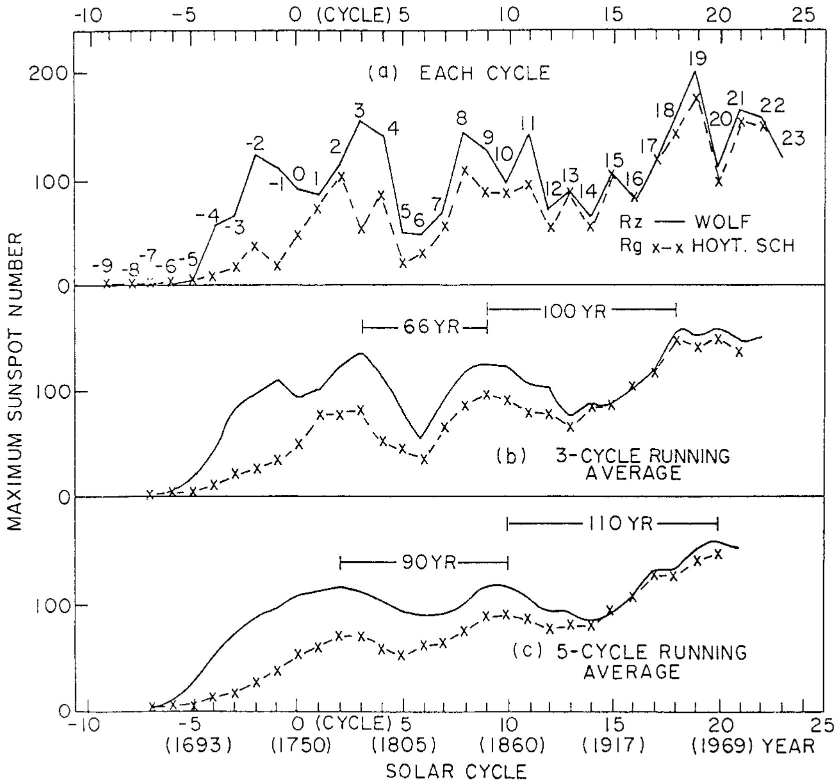

Figure 4. Plot of sunspot maxima for cycles (−9 to +22) for Wolf sunspot number *Rz* (full lines) and Hoyt and Schatten (1998) index *Rg* (crosses) for (a) individual cycle values, (b) 3-cycle running averages, (c) 5-cycle running averages.

geneous series called Group Sunspot Numbers *Rg*, and provided random and systematic error estimates. Their major conclusion was that solar activity for 1700–1882 was lower than that obtained by Wolf, by 25–50%. The activity was poorly determined before 1653, accurate during 1654–1727, uncertain by up to 15 –20% (or unknown) during 1728–1800, had a ~5% accuracy during 1800–1850, and a 1–2% accuracy for 1851 to the present. If true, the results presented in the present paper could be erroneous, as Wolf *Rz* data have been used right from cycle 1 (1755 onwards). In Figure 4, the full lines refer to Wolf's sunspot number *Rz* while crosses and dashes represent the *Rg* values of Hoyt and Schatten (1998). As can be seen, the *Rg* values are quantitatively lesser than the *Rz* values (more so before 1850) but the patterns remain the same qualitatively, with the swings 66, 100 yr in (b) and 90, 110 yr in (c). Thus, the revised data *Rg* only indicate a lower level in earlier years, but the relative values retain the earlier patterns qualitatively. In Table I, the values of *Rg* are also given. When *Rg*(max) values were plotted against aa(min), the plot (not shown here) was very similar to Figure 1, and, using data for cycles 9–22, the predicted *Rg*(max) for cycle 23 was 131 ± 31 as against

TABLE I

The *aa*(min) and *R*(max) obtained from 12-month running means of *aa* index and Wolf sunspot numbers *R*, the year and month when these occurred, and the *Rz* and *Rg* values reported by Hoyt and Schatten (1998) for those years.

Cycle	*aa*(min) year (month)	12-month *aa*(min)	*R*(max) year (month)	12-month *R*(max)	*Rz*	*Rg*	*Rz* minus *Rg*
1			1761(6)	86.5	85.9	74	11.9
2			1769(9)	115.8	106.1	102.4	3.7
3			1778(5)	158.5	154.4	53.1	101.3
4			1788(2)	141.2	130.9	83.2	47.7
5			1805(2)	49.2	42.2	19.8	22.4
6			1816(5)	48.7	45.8	31.3	14.5
7			1829(9)	71.7	67.0	59.3	7.7
8			1837(3)	146.9	138.3	109.9	28.4
9	1845(6)	14.1	1848(2)	131.6	124.7	86.0	38.7
10	1856(6)	10.3	1860(2)	97.9	95.8	85.6	10.2
11	1867(6)	16	1870(8)	140.5	139.0	96.2	42.8
12	1878(12)	6.6	1883(12)	74.6	63.7	54.7	9
13	1890(7)	10.6	1894(1)	87.9	78.0	88.0	−10
14	1900(11)	5.9	1906(2)	64.2	53.8	56.2	−2.4
15	1913(8)	8.2	1917(8)	105.4	103.9	110.1	−6.2
16	1924(9)	9.2	1928(4)	78.1	77.8	82.3	−4.5
17	1934(5)	13.1	1937(4)	119.2	114.4	120.6	−6.2
18	1945(6)	16.3	1947(5)	151.8	151.6	144.9	6.7
19	1955(4)	16.8	1958(3)	201.3	184.8	175.1	9.7
20	1965(5)	13.7	1968(11)	110.6	105.9	98.2	7.7
21	1980(3)	17.1	1979(12)	164.5	155.4	155.7	−0.3
22	1986(12)	17.4	1989(7)	158.5	157.7	147.7	10
23	1997(8)	15.7					

149 ± 24 for *Rz*(max). It may be some consolation for Hoyt and Schatten (1998) that the observed value 122 is nearer to the predicted *Rg*(max) 131, as compared to predicted *Rz*(max) 149.

6. Mechanisms

During the last two decades, considerable effort has been made by several groups for understanding the relationship between solar and geomagnetic activities and predicting the strength of sunspot cycles. Geomagnetic activity is related to solar activity through the solar wind. Feynman (1982) showed that the 11-year solar cycle as expressed by the number of sunspots is very different from the 11-year solar cycle as expressed by the solar wind and geomagnetics. She decomposed the solar wind cycle into 2 components, an (R) component having similar phase and amplitude as the sunspot cycle, and an (I) component having similar amplitudes but 5–6 years out of phase. The source of the (R) component is sporadic or short-lived solar events, while the (I) component is due to long-lived solar features such as coronal holes. Legrand and Simon (1991) studied the response of the geomagnetic field to solar wind fluctuations, the effective solar wind parameters being the total magnetic field B and the wind velocity V, or rather their combination BV^2. However, Kane (1997) noticed that the correlation between aa index and solar wind velocity was $+0.91$ for cycle 20, but only $\sim +0.75$ for cycles 21 and 22, indicating the influence of some other factors. Whereas sunspot numbers rise steadily to the maximum and then fall steadily to a low level during each sunspot cycle, the geomagnetic indices Ap or aa show two maxima per cycle, one near or before the sunspot maximum and the other in the declining phase. This structure (gap between the two maxima, called the Gnevyshev gap) results in the quasi-biennial and quasi-triennial periodicities observed in the geomagnetic indices (Kane, 1997b). Recently, Ahluwalia (2000) pointed out that the Gnevyshev gap coincided with the solar polar field reversals (polarities changing from N to S or *vice versa*), which generally occur at sunspot maxima.

For the Ohl (1966) hypothesis, Schatten *et al.* (1978) offered a plausible explanation based on the 'solar dynamo theory', wherein the solar polar field serves as a seed for future solar activity. These authors developed a solar dynamo amplitude (SODA) index which described the amount of the buoyant solar magnetic flux and, using the SODA index, Schatten, Meyers, and Sofia (1996) predicted a value (138 ± 30) for cycle 23, which has turned out to be reasonably accurate. It seems that the magnetic structure of the Sun is of vital importance and needs further study. On the other hand, all large estimates have proved erroneous and the basis for the larger estimates needs reexamination and rethinking.

7. Conclusion

The predicted values for the maximum of solar cycle 23 (1996 onwards) were in a very wide range, ~80–210. Cycle 23 seems to have peaked in 2000, with a smoothed sunspot number maximum of ~122. From about 20 predictions, only 8 were within 122 ± 20. There is some indication that a long-term oscillation of ~80–100 years may be operative and might have peaked near cycle 20 (1970), implying that cycles in the near future may be smaller and smaller for the next 50 years or so, rebounding thereafter for the next 50 years or so.

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