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A Preliminary Estimate of the Size of the Coming Solar Cycle 24, based on Ohl's Precursor Method

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Abstract For many purposes (*e.g.*, satellite drag, operation of power grids on Earth, and satellite communication systems), predictions of the strength of a solar cycle are needed. Predictions are made by using different methods, depending upon the characteristics of sunspot cycles. However, the method most successful seems to be the precursor method by Ohl and his group, in which 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. In the present communication, the method is illustrated by plotting the 12-month running means *aa*(min) of the geomagnetic disturbance index *aa* near sunspot minimum versus the 12-month running means of the sunspot number Rz near sunspot maximum [*aa*(min) versus Rz(max)], using data for sunspot cycles 9 – 18 to predict the Rz(max) of cycle 19, using data for cycles 9 – 19 to predict Rz(max) of cycle 20, and so on, and finally using data for cycles 9 – 23 to predict Rz(max) of cycle 24, which is expected to occur in 2011 – 2012. The correlations were good ($\sim$+0.90) and our preliminary predicted Rz(max) for cycle 24 is 142 ± 24, though this can be regarded as an upper limit, since there are indications that solar minimum may occur as late as March 2008. (Some workers have reported that the *aa* values before 1957 would have an error of 3 nT; if true, the revised estimate would be 124 ± 26.) This result of the precursor method is compared with several other predictions of cycle 24, which are in a very wide range (50 – 200), so that whatever may be the final observed value, some method or other will be discredited, as happened in the case of cycle 23.

1. Introduction

Zurich relative sunspot number (Rz) is usually used as an index of solar activity, which shows a predominant $\sim$11-year cycle. A few decades back, characteristics of the 11-year cycle were of mere academic curiosity; but in the present satellite age, the strength of the solar cycle makes a huge difference to satellite operators, who plan their launches many years in advance. As mentioned by Henson and Hosansky (2006), each solar peak heats and

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expands the outer atmosphere, which in turn increases the drag on satellites, especially those in low-Earth orbits. Hence, satellite planners time their missions and adjust orbital heights to take advantage of weak solar activity, if possible. Occurrence of a solar peak earlier or later or of unexpectedly large magnitude could alter the expected useful life of the satellite. Predictions of the solar activity are also useful for other purposes, such as operation of power grids on Earth and satellite communication systems.

Sunspot values are available since about 1700 (Waldmeier, 1961), but the quality of the data is considered "poor" during 1700 – 1748, "questionable" during 1749 – 1817, "good" during 1818 – 1847, and "reliable" from 1848 onward (McKinnon, 1987). A sunspot cycle is defined as occurring from one sunspot minimum to the next. Cycle 1 occurred in the period 1755 – 1765. Predictions are based on some characteristics of the sunspot activity in successive cycles. Hathaway and Wilson (2004) mention that the sunspot record shows that (i) sunspot cycles have periods of 131 ± 14 months with a normal distribution; (ii) sunspot cycles are asymmetric with a fast rise and slow decline; (iii) the rise time from minimum to maximum decreases with cycle amplitude; (iv) large-amplitude cycles are preceded by short-period cycles; (v) large-amplitude cycles are preceded by high minima; (vi) although the two hemispheres remain linked in phase, there are significant asymmetries in the activity of the two solar hemispheres; (vii) the rate at which the active latitudes drift toward the solar equator is anticorrelated with the cycle period; (viii) the rate at which the active latitudes drift toward the equator is positively correlated with the amplitude of the cycle after the next; (ix) there has been a significant secular increase in the amplitudes of the sunspot cycles since the end of the Maunder Minimum (year 1715); and (x) there is weak evidence for a quasi-periodic variation in the sunspot cycle amplitudes with a period of about 90 years. For cycle 23, there were many predictions based on different criteria. 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 sunspot number variations for many years. They observed that group (i) had high values and group (ii) had moderate and low values. Soon after, NOAA's Space Environment Center (SEC) recruited a scientific panel to assess the likely development of cycle 23 and their report entitled "Solar Cycle 23 Project: Summary and Panel Findings," later published as Joselyn *et al.* (1997), mentioned (i) a range of 160 – 200 of Rz(max) of cycle 23 as obtained by considering the even/odd behavior and (ii) a range 110 – 160 of Rz(max) by other methods. Their summary table is reproduced here as Table 1.

Although four of the six techniques are in general agreement, the panel gave the greatest weight to *precursor methods*, since they have proved to be the most successful technique for solar activity predictions in the past. These methods utilize the concept of an "extended solar cycle," the idea that the imminent solar cycle actually starts in the declining phase of

Table 1 Combined forecasts of maximum smoothed sunspot number for cycle 23, for classes of prediction techniques.

Technique	Low end of range	Maximum	High end of range
Even/odd behavior	165	200	235
Precursor	140	160	180
Spectral	135	155	185
Recent climatology	125	155	185
Neural networks	110	140	170
Climatology (all)	75	115	155

the previous cycle. In the declining phase and at solar minimum, the coming cycle manifests itself in the occurrence of structures such as coronal holes and the strength of the solar polar magnetic field. High-speed solar wind streams from low-latitude coronal holes give rise to recurrent geomagnetic disturbances that are used as the predictor of the strength of the next cycle (*e.g.*, Thompson, 1993, 1996). The precursor methods invoke a solar dynamo concept, whereby the polar field in the declining phase and at minimum is the seed of future toroidal fields within the Sun that will cause solar activity (*e.g.*, Schatten and Pesnell, 1993). The dependence on the strength of the solar polar field also offers an explanation of why geomagnetic precursors serve as proxies for predicting the solar cycle. A physical connection exists among the polar field, coronal holes, the interplanetary field, and geomagnetic activity.

During the past decade, many other predictions have been made based on (a) the geomagnetic field, (b) solar magnetic fields, coronal holes, *etc.*, (c) time series studies and neural networks, and (d) other and/or mixed methods. For cycle 24, Dean Pesnell compiled 30 predictions, obtained by different methods (private communication). The values have a very wide range of 70 – 180. However, using precursor methods, Schatten (2005) mentions 80 ± 30 (based on the polar field in the declining phase and at minimum) while Hathaway and Wilson (2006) mention 160 ± 25 (based on analysis of geomagnetic *aa* indices).

In one of the precursor methods (Ohl's method), geomagnetic *aa* indices at solar minimum are seen to be well correlated with the succeeding Rz(max) (Ohl, 1966, 1976; Brown and Williams, 1969; Ohl and Ohl, 1979; Sargent, 1978). Since then, Kane (1978, 1987, 1992, 1997, 1998), Wilson (1988a, 1988b, 1992), and Wilson, Hathaway, and Reichmann (1998) have been studying this aspect for the past three decades. Presently (2006 – 2007), though solar activity is occasionally still high, we consider that sunspot numbers Rz (12-month running means) may have reached (or are near) a minimum, and the *aa* indices (12-month running means) seem to have reached a minimum. Thus, the method can be used for prediction of Rz(max) of cycle 24. In the present communication, the method is illustrated for recent cycles 19 – 23 and used for cycle 24.

2. Data

The data used are the geomagnetic *aa* indices (the antipodal amplitudes deduced from the K index of Greenwich, England, and Melbourne, Australia; Mayaud, 1973) and sunspot numbers Rz (McKinnon, 1987, and further data from the Web sites ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/RELATED_INDICES/AA and ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS). For *aa* indices, data are available from 1868 onward 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). Hence, we have now *aa* data for cycle 9 and 10 (annual values) and for cycle 11 (monthly values) onward.

3. Plots

The monthly values of Rz and *aa* indices vary erratically from month to month. Hence, 12-month running means were evaluated and used. Figure 1 shows the plots of the 12-month running means of Rz and *aa* indices near sunspot minima for the beginnings of cycles 12 – 24. In general, the *aa*(min) occurs anywhere from 2 – 3 months before to several months

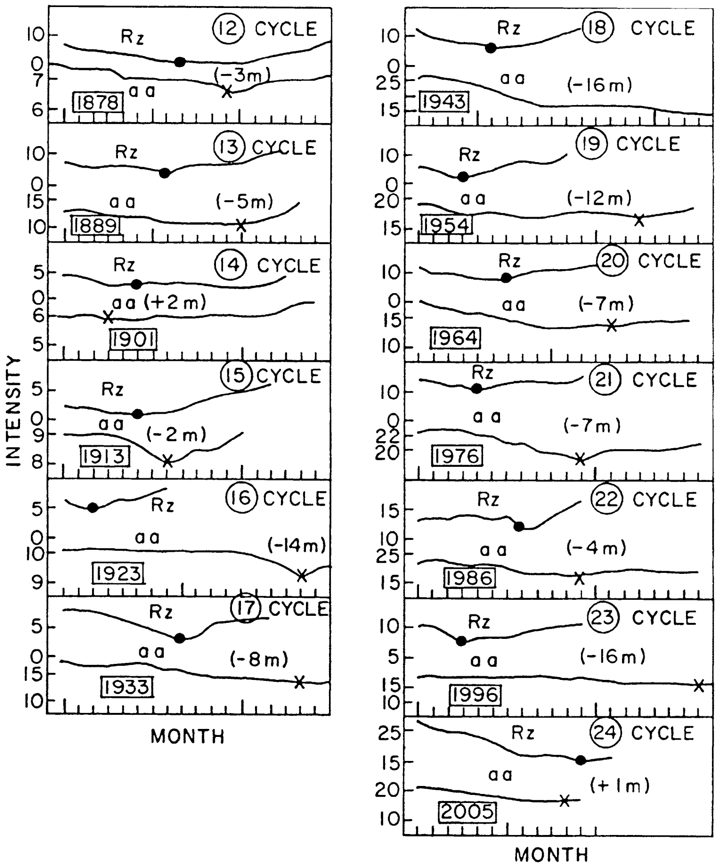

Figure 1 Plots of the 12-month means of sunspot number Rz and geomagnetic disturbance indices *aa* near sunspot minima for the beginnings of cycles 12 – 24. Rz(min) are marked by big dots and *aa*(min) by crosses. In the plot of cycle 24, the starting month is June 2005, the 12-month mean value of *aa*(min) (cross) is at May 2006, and the probable 12-month mean value of Rz(min) (big dot) is at October 2006.

later than Rz(min) (mostly later). For cycle 24 (starting month June 2005), the Rz monthly values available up to April 2007 have yielded 12-month running means as 15.2 centered at June 2006, 15.3 centered at July 2006, 15.8 centered at August 2006, 15.3 centered at September 2006, and 13.1 centered at October 2006, thus indicating (tentatively) that the 12-month mean of Rz minimum might have occurred centered in October 2006. The *aa* monthly values available up to January 2007 yielded 12-month running means centered at January, February, March, April, May, June, and July 2006 as 17.4, 16.8, 15.5, 15.6, 15.5, 16.2, and 16.6, indicating that the 12-month mean of *aa* minimum may have occurred centered at May 2006. The *early* occurrence of *aa*(min) by as much as five months compared to sunspot minimum leaves some doubt about its genuineness. We suspect that this may be a false signal and *aa* values may drop again to a new minimum. However, this will be confirmed only in the next few months when *aa* values start rising further. Till then, *aa*(min) $= 15.5$ would be the value to use for a preliminary prediction of Rz(max) of cycle 24.

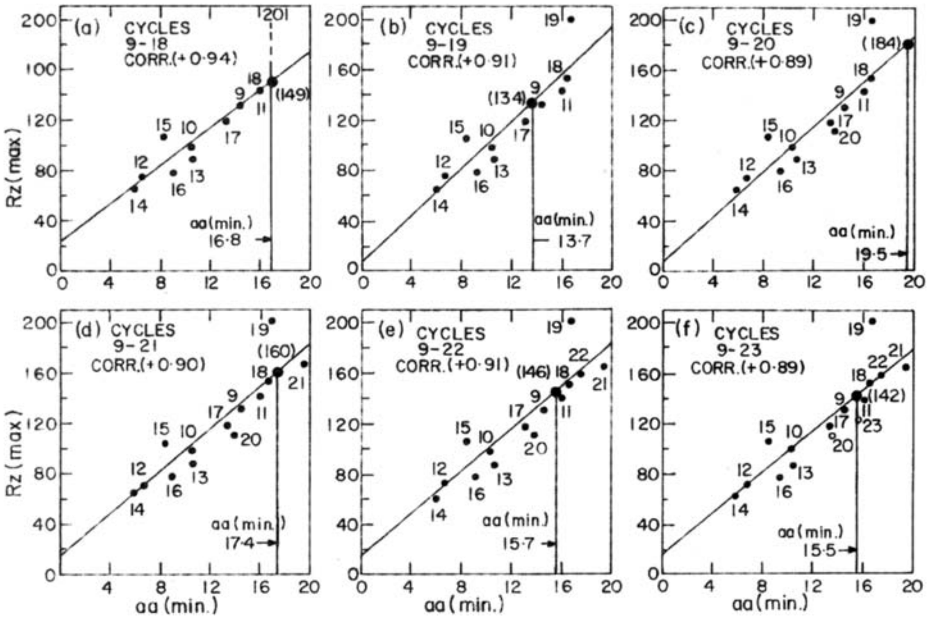

Figure 2 Plots of 12-month running means of aa(min) at the beginning of a cycle versus the Rz(max) that occurred a few years later in that cycle only for cycle 19 onward so that at least 10 pairs of points are available. (a) Ten pairs of points for cycles 9 – 18, (b) 11 pairs of points for cycles 9 – 19, (c) 12 pairs of points for cycles 9 – 20, (d) 13 pairs of points for cycles 9 – 21, (e) 14 pairs of points for cycles 9 – 22, and (f) 15 pairs of points for cycles 9 – 23. The straight lines in each plot are the regression lines for which the correlations ($\sim$+0.90 ± 0.06) are indicated. In each plot, the vertical line indicates the aa(min) used for predicting the Rz(max) of the next cycle. Finally, the prediction for the coming cycle 24 is in plot (f).

Figure 2 shows the plots of aa(min) at the beginning of a cycle versus the Rz(max) that occurred a few years later in that cycle. The 12-month running means of the data pairs Rz(max) : aa(min) are available for cycle 9 onward but plots are shown only for cycle 19 onward so that at least 10 pairs of points are available. Figure 2a refers to the 10 pairs of points for cycles 9 – 18. The points are very well correlated (+0.94 ± 0.06) and, using standard statistical methods (Bevington, 1969), a linear regression equation of a type $y = A + Bx$, where $y = Rz(\text{max})$ and $x = aa(\text{min})$, was obtained as follows:

$$Rz(\text{max}) = (21.8 \pm 11.1) + (7.6 \pm 1.0)aa(\text{min}). \quad (1)$$

The coefficients A and B, their standard deviations σ_A and σ_B, the value $aa(\text{min}) = 16.8$ at the beginning of cycle 19, the predicted $Rz(\text{max}) = 149$ with its standard error for cycle 19, and its comparison with the observed value are all shown in the first row of Table 2. Using $aa(\text{min}) = 16.8$, we find that the vertical line in Figure 2a meets the regression line and indicates a predicted value of $Rz(\text{max}) = 149 \pm 20$, which is far below the observed value of 201 for cycle 19. Thus, for cycle 19, the prediction was *unsatisfactory* (with the observed value 35% above the expected one). Cycle 19 was an abnormally large cycle (largest on record) and most of the predictions about this cycle have proved grossly erroneous.

Figure 2b shows plots for 11 points of cycles 9 – 19. The correlation is +0.91 ± 0.06. The correlation coefficients are shown in the second row of Table 2. Using $aa(\text{min}) = 13.7$

Table 2 Regression coefficients and predictions of Rz(max) using aa(min).

Cycles	Pairs	Correlation ±0.06	A	σ_A	B	σ_B	For next cycle aa(min)	Rz pred.	σ_{Rz}	Rz obs.	Dev. Rz (%)
9–18	10	+0.94	21.8	11.1	7.6	1.0	16.8	149	20	201	35
9–19	11	+0.91	5.9	17.7	9.3	1.5	13.7	134	27	111	−17
9–20	12	+0.89	7.4	18.1	9.1	1.5	19.5	184	34	165	−10
9–21	13	+0.90	13.9	16.2	8.4	1.3	17.4	160	27	159	−1
9–22	14	+0.91	14.1	15.2	8.4	1.1	15.7	146	23	122	−16
9–23	15	+0.89	16.0	15.5	8.1	1.2	15.5	142	24	?	

for the beginning of cycle 20, we find that the vertical line in Figure 2b meets the regression line and indicates a predicted value of $Rz(\max) = 134 \pm 27$, which is slightly above the observed value of 111 for cycle 20 (so the observed value is 17% below the expected value).

Figure 2c shows plots for 12 points of cycles 9–20. The correlation is $+0.89 \pm 0.06$. The correlation coefficients are shown in the third row of Table 2. Using $aa(\min) = 19.5$ for the beginning of cycle 21, we find that the vertical line in Figure 2c meets the regression line and indicates a predicted value of $Rz(\max) = 184 \pm 34$, which is above the observed value of 165 for cycle 21 (so the observed value is 10% below the expected one).

Figure 2d shows plots for 13 points of cycles 9–21. The correlation is $+0.90 \pm 0.06$. The correlation coefficients are shown in the fourth row of Table 2. Using $aa(\min) = 17.4$ for the beginning of cycle 22, we find that the vertical line in Figure 2d meets the regression line and indicates a predicted value of $Rz(\max) = 160 \pm 27$, which is almost exactly the same as the observed value of 159 for cycle 22.

Figure 2e shows plots for 14 points of cycles 9–22. The correlation is $+0.91 \pm 0.06$. The correlation coefficients are shown in the fifth row of Table 2. Using $aa(\min) = 15.7$ for the beginning of cycle 23, we find that the vertical line in Figure 2e meets the regression line and indicates a predicted value of $Rz(\max) = 146 \pm 23$, which is above the observed value of 122 for cycle 23 (so the observed value is 16% below the expected one).

Figure 2f shows plots for 15 points of cycles 9–23. The correlation is $+0.89 \pm 0.06$. The correlation coefficients are shown in the sixth row of Table 2. Using $aa(\min) = 15.5$ for the beginning of cycle 24, we find that the vertical line in Figure 2f meets the regression line and indicates a predicted value of $Rz(\max) = 142 \pm 24$. This has to be compared with the observed value of Rz(max) of cycle 24, which will occur later in the next few years, probably in 2010–2011. The regression equation for cycle 9–23 is

$$Rz(\max) = (16.0 \pm 15.5) + (8.1 \pm 0.1.2)aa(\min). \tag{2}$$

Recently, some workers (*e.g.*, Svalgaard, Cliver, and Le Sager, 2004; Jarvis, 2005; Martini, 2006) have suggested that the index *aa is in error* and should be increased by 3 nT before 1957. This is a serious matter as *aa* values at sunspot minimum are about 20 nT or less and an error of 3 nT would be substantial. Table 3 gives the aa(min) values we have used so far and the new set of values of aa(min) by adding 3 nT to values up to April 1955, *i.e.*, up to the beginnings of cycle 9–19, and retaining the earlier values for cycles 20–23.

With the new values of aa(min), the regression equation using data for cycles 9–23 was

$$Rz(\max) = (-24.9 \pm 18.1) + (9.6 \pm 0.1.2)aa(\min). \tag{3}$$

Table 3 Values of aa(min) and Rz(max) and their timings [year (month)] of occurrence for cycles 9 – 24. For aa(min), the last three columns give prediction results using aa(min) (revised) (*i.e.*, increased by 3 nT for earlier cycles 9 – 19).

Rz(max) Year (month)	aa(min) Year (month)	Cycle	aa(min)	Obs. Rz(max)	Pred. Rz(max)	Error (%)	Revised aa(min)	Revised Pred. Rz(max)	Error (%)
1848 (February)	1845 (June)	9	14.1	132			17.1		
1860 (February)	1856 (June)	10	10.3	98			13.3		
1870 (August)	1867 (June)	11	16	141			19		
1883 (December)	1878 (December)	12	6.6	75			9.6		
1894 (January)	1890 (July)	13	10.6	88			13.6		
1906 (February)	1900 (November)	14	5.9	64			8.9		
1917 (August)	1913 (August)	15	8.2	105			11.2		
1928 (April)	1924 (September)	16	9.2	78			12.2		
1937 (April)	1934 (May)	17	13.1	119			16.1		
1947 (May)	1945 (June)	18	16.3	152			19.3		
1958 (March)	1955 (April)	19	16.8	201	149	35	19.8	149	35
1968 (November)	1965 (May)	20	13.7	111	134	−17	13.7	106	4
1979 (December)	1976 (December)	21	19.5	165	184	−11	19.5	160	3
1989 (July)	1986 (December)	22	17.4	159	160	−1	17.4	141	13
2000 (March)	1997 (August)	23	15.7	122	146	−17	15.7	127	−4
	2006 (March)	24	15.5		142		15.5	124	

The correlation was 0.92 ± 0.06, slightly better than the $+0.89 \pm 0.06$ obtained for Equation (2), and now, the new prediction for cycle 24 is $Rz(\max) = 124 \pm 26$, smaller than the earlier prediction $Rz(\max) = 142 \pm 24$ from Equation (2). New predictions for earlier cycles 19 – 23 are given in the last columns of Table 3. For cycle 19, the prediction remains unsatisfactory (with an error of 35%), but for cycles 20 – 23, the errors are less than before.

4. Comparison with Results of Other Workers

As mentioned in Table 2, the observed and expected values of Rz(max) were 201 and 149 (cycle 19), 111 and 134 (cycle 20), 165 and 184 (cycle 21), 159 and 160 (cycle 22), and 122 and 146 (cycle 23). Thus, except for cycle 19, the match was within 20% for cycles 20 – 23 and for cycle 24, a prediction is given as $Rz(\max) = 142 \pm 24$. If aa(min) values before 1957 are considered erroneous and increased by 3 nT for cycles 9 – 19, the new prediction becomes $Rz(\max) = 124 \pm 26$. These values (old and new) can be compared to the predictions of other workers for cycle 24 as given in a table prepared by W.D. Pesnell (private communication) and in tables prepared by Janssens (http://members.chello.be/j.janssens/SC24.html) and by Lundstedt (http://www.lund.irf.se/rwc/cycle24/). [A Solar Cycle 24 Prediction Panel composed of international scientists and presided by Douglas Biesecker (http://www.sec.noaa.gov/SolarCycle/SC24/index.html) issued on 25 April 2007, a consensus opinion that the cycle would commence in March 2008 (±6 months) and *two* consensus opinions, that the solar maximum would be 140 ± 20 in October 2011 or 90 ± 10 in August 2012.] Predictions, differing widely in cycle onset, duration, and intensity, are reported in these tables; some are based on physical grounds whereas others are statistical. In these, many diverse predictions are claimed to be based on solid physical grounds. Hence, a "consensus" may not be very meaningful. For cycle 23, Joselyn *et al.* (1997) had given a consensus opinion of a *large* solar cycle with a smoothed sunspot maximum of 160 (the observed value was 122) and a minimum during April 1996 – March 1997, likely in late 1996 (and occurred in April 1996).

4.1. Physical Analysis (Including Precursor Methods)

(1) Using the same methodology as ours, namely, using *aa*(min) as a precursor, Hathaway and Wilson (2006) reported a prediction value of $Rz(\max) = 160 \pm 25$. This is larger than our estimate of 142 ± 24, probably because they used an *aa*(min) value of 2005 – 2006 when *aa* values were still large.
(2) Using the Sun's polar field as a precursor of solar activity on the basis of dynamo physics (SODA index), Schatten (2005) predicted 80 ± 30. Svalgaard, Cliver, and Kamide (2005) also used solar polar fields and predicted 75 ± 8.
(3) Thompson (1993, 1996) had outlined a precursor method where geomagnetic disturbances correlate well with the sum of the amplitudes of the current cycle and the next and predicted a value of 164 for cycle 23 (vs. an observed value of 122). For cycle 24, his preliminary prediction seems to be of a much smaller cycle than cycle 23. We set it as ∼110.
(4) Duhau (2003) found a nonlinear coupling function between sunspot maximum and *aa* minimum modulations and estimated the maximum sunspot number in cycle 24 as 88 ± 24.
(5) Dikpati, de Toma, and Gilman (2006) used a modified flux-transport solar dynamo model and predicted $Rz(\max)$ of 155 – 180.
(6) Hathaway and Wilson (2004) assumed that a fast (solar) meridional circulation speed during cycle 22 would lead to a strong solar cycle 24 of $Rz(\max) = 145 \pm 30$.
(7) Sello (2003) used a precursor method and reported $Rz(\max) = 96 \pm 25$.
(8) Clilverd *et al.* (2004) predicted a *weak* cycle [$Rz(\max) = \sim 45$], based on the variation of the atmospheric cosmogenic radiocarbon.
(9) Chopra and Dabas (2006) used a modified version of the precursor method (using geomagnetic indices *before* sunspot minimum) and predicted $Rz(\max) = 140 \pm 6$.
(10) Jain (2006) used a modified version of the precursor method (using geomagnetic indices *before* sunspot minimum) and predicted $Rz(\max) = 144 \pm 18$.
(11) Maris, Popescu, and Besliu (2004) used flare energy release during the descending SC phase and predicted $Rz(\max)$ = low value (which we set as ∼70).

4.2. Spectral Analysis

(i) Tsirulnik, Kuznetsova, and Oraevsky (1997), using a new method of nonlinear spectral analysis (the method of global minimum, MGM), predicted $Rz(\max) = 180$.
(ii) Gholipour *et al.* (2005) used spectral analysis and made a neurofuzzy prediction of $Rz(\max) = 145$.
(iii) Echer *et al.* (2004) used spectral analysis and made a prediction of $Rz(\max) = 116 \pm 13$.
(iv) Clilverd *et al.* (2006) used spectral analysis and predicted a very low $Rz(\max) = 42 \pm 34$.
(v) Nordemann *et al.* (2007) used spectral analysis of sunspot series and predicted $Rz(\max) = \sim 100$.

4.3. Statistical Analysis Including Neural Networks

(i) Kim, Wilson, and Cucinotta (2004) performed a statistical analysis of cycle parameters and predicted $Rz(\max) = 122 \pm 6$.
(ii) Sello (2003) used a nonlinear prediction method and predicted $Rz(\max) = 115 \pm 21$.
(iii) Lantos (2006) used skewness of previous cycles separated into even/odd cycles and predicted $Rz(\max) = 108 \pm 38$.
(iv) Kane (1999) extrapolated dominant spectral components and obtained a prediction of $Rz(\max) = 105 \pm 9$.
(v) Wang *et al.* (2002) used statistical characteristics of solar cycles and predicted $Rz(\max) = 101 \pm 18$.
(vi) Horstman (2005) used the average of the past five historical cycles and predicted $Rz(\max) = 185$.
(vii) Badalyan, Obridko, and Sykora (2001) used statistics of the λ 5303 Å coronal line and estimated $Rz(\max) < 50$.
(viii) Maris and Oncica (2006) used neural networks and reported $Rz(\max) = 145$.
(ix) Lundstedt (2006), based on neural networks and physics, predicted $Rz(\max) = 85 \pm 25$.
(x) Du (2006) and Du, Wang, and He (2006), based on intercycle analysis, predicted $Rz(\max) = 150 \pm 22$.
(xi) Javaraiah (2007), based on hemispheric sunspot area, predicted $Rz(\max) = 74 \pm 10$.
(xii) Li, Gao, and Su (2005) used a statistical method but concluded that the amplitude would be 189.9 ± 15.5, if the cycle is a fast riser, or about 136, if it is a slow riser. Thus, one will have to wait for the cycle to evolve.

4.4. Other Predictions Available as Abstracts or Private Information

(a) Podladchikova, Lefebvre, and Van der Linden used the integral of sunspot number as a precursor and predicted a range of 152 – 197 for $Rz(\max)$.
(b) Pesnell compared cycle $n+1$ with cycle n *etc.* and predicted $Rz(\max) = 120 \pm 45$ and 115 ± 40.
(c) Prochasta used the mean of several cycles and predicted $Rz(\max) = 114 \pm 43$.
(d) Kennewell and Patterson averaged eight solar cycles and predicted $Rz(\max) = 134 \pm 50$.
(e) Roth used an autoregressive moving-average process and predicted $Rz(\max) = 92 \pm 28$.
(f) Baranovski used the mathematical theory of nonlinear dynamics and predicted $Rz(\max) = 80 \pm 21$.
(g) Euler and Smith used a modified McNish – Lincoln model and predicted $Rz(\max) = 110 \pm 70$.
(h) Kontor made a statistical Gaussian-based extrapolation and predicted $Rz(\max) = 70 \pm 18$.
(i) Tlatov gave the weighted average of four predictions as $Rz(\max) = 114 \pm 7$.
(j) Choudhuri, based on solar polar field, predicted $Rz(\max) = 85$.
(k) Kaftan, based on kinematical modeling of solar parameters, predicted $Rz(\max) = 163 \pm 37$.
(l) Ahnert, statistically, predicted $Rz(\max) = 92 \pm 30$.
(m) Hiremath, using statistical methods, predicted $Rz(\max) = 110$.

(n) The IPS Radio and Space Services (Australian Government, http://www.ips.gov.au/mailman/listinfo/) made a prediction based on the average of the past nine solar cycles (cycles 15 to 23) of $Rz(\max) = 134 \pm 50$.
(o) Sun *et al.*, using statistical characteristics of solar cycles, predicted $Rz(\max) = 110 \pm 18$.

5. Conclusions and Discussion

Zurich relative sunspot number (Rz) is an index of solar activity, which shows a predominant ∼11-year cycle. In the present satellite age, satellite operators plan their launches many years in advance to minimize satellite drags. Hence, predictions of solar activity are needed. Predictions are also useful for other purposes such as operation of power grids on Earth and satellite communication systems.

Predictions are made using different methods, all depending upon one or more characteristics of sunspot cycles. However, the method most successful seems to be the precursor method by Ohl and his group, whereby the geomagnetic activity in the declining part of a sunspot cycle is found to be well correlated with the sunspot maximum of the next cycle. In the present communication, the method is illustrated by plotting the 12-month running means of the geomagnetic disturbance index *aa* near sunspot minimum versus the 12-month running means of sunspot number Rz near sunspot maximum [$aa(\min)$ versus $Rz(\max)$] using data for sunspot cycles 9 – 18 and using the regression equation to predict the $Rz(\max)$ of cycle 19, then using data for cycles 9 – 19 to predict $Rz(\max)$ of cycle 20 and so on, and finally using data for cycles 9 – 23 to predict $Rz(\max)$ for the forthcoming cycle 24, which is likely to occur in 2010 – 2011. The correlations were good ($+0.90 \pm 0.06$) and the predicted $Rz(\max)$ for cycle 24 is 142 ± 24. [This is very close to the values of 140 ± 6 estimated by Chopra and Dabas, 2006 and 144 ± 18 by Jain, 2006, using a modified precursor method where geomagnetic indices *prior* to the sunspot minimum are used.] If $aa(\min)$ values before 1957 are considered as erroneous (Svalgaard, Cliver, and Le Sager, 2004; Jarvis, 2005; Martini, 2006) and are increased by 3 nT for cycles 9 – 19, *our prediction is lower, namely*, $Rz(\max) = 124 \pm 26$.

Our results of 142 ± 24 (or 124 ± 26, if *aa* values are in error by 3 nT before 1957) by the precursor method can be compared with other predictions of cycle 24, which range from (a) <70 (three predictions), (b) 70 – 90 (eight predictions), (c) 90 – 110 (eight predictions), (d) 110 – 130 (ten predictions), (e) 130 – 150 (seven predictions), (f) 150 – 170 (three predictions), and (g) >170 (four predictions). Our prediction of 142 ± 24 is in the (e) range of 130 – 150, and our prediction of 124 ± 26 is in the (d) range of 110 – 130, and the average of all predictions (∼115) is in the (d) range of 110 – 130. Thus, if our predictions come true, predictions in the high range (g) (Dikpati, Tsirulnik, Horstman, and Podladchikova) as well as in the low range (a) (Clilverd and Badalyan) would prove erroneous. If the observed value exceeds 150 (is below 90), all the lower (higher) ranges would prove erroneous. The ambiguity occurs because, though prominent scientific workers have made detailed studies of restricted aspects of solar physics (flux transport, magnetic fields, *etc.*), the time evolution of these and their implication for overall sunspot activity are not yet well understood. Though the achievements so far are considerable, much more needs to be done. Presently, the situation is similar to that of the proverbial seven blind men trying to describe an elephant, each examining a different part of the elephant (legs, tail, trunk, *etc.*).

It may be noted that the 12-month running means of sunspot number Rz and *aa* index have apparently reached their minima during 2006; but the (very likely) possibility remains that $a_{a(\mathrm{min})}$ *may decrease further.* In that case, our present estimates of 142 ± 24 or 124 ± 26 will be preliminary estimates (upper limits) and will have to be reduced. [This has happened before for cycle 23; see Kane, 1998.] For the present, one can only watch for future developments.

Of particular interest will be the predictions of Dikpati, de Toma, and Gilman (2006) based on a modification of a calibrated flux-transport solar dynamo model, which predicts that cycle 24 will have a 30 – 50% higher peak than cycle 23 (which had 122). Thus, a value in the range ∼160 – 185 is expected, greater than our 142 ± 24 (and far greater than our 124 ± 26). However, Svalgaard, Cliver, and Kamide (2005) and Schatten (2005) predict a value of 70 – 80, which is far less than our 142 ± 24 or 124 ± 26. Thus, the credibility of one of these models is at stake.

In some publications, not only the expected maximum of cycle 24 is given but that of cycle 25 is also mentioned. Thus, Hathaway and Wilson (2004) mention 145 ± 30 for cycle 24 in 2010 and only 70 ± 30 for cycle 25 in 2023. Du (2006) mentions 150 ± 22 for cycle 24 and 103 ± 22 for cycle 25. Schatten and Tobiska (2003) claim that solar activity will decrease after cycle 24 and will be heading for a Maunder Minimum in the next few decades. Duhau (2003) mentions that solar activity is in a declining episode that started about 1993. A very similar prediction has more recently been made by Clilverd (2005) based on modeling of low-frequency solar oscillations, who say that the peak sunspot prediction for cycle 24 will be significantly smaller than cycle 23, and peak sunspot numbers are predicted to be $\sim 45 \pm 27$. However, the model also predicts a *recovery* during the middle of the century to more typical solar activity cycles with peak sunspot numbers of ∼120.

Some predictions are based on odd/even behaviors, but Ahluwalia (1998) has given a new twist to this pattern by pointing out that there is possibly a *three-cycle (∼33-years)* quasi-periodicity involved. Thus, cycle 17 was low (119) whereas cycles 18 (152) and 19 (201) were higher; cycle 20 was low (111), and cycles 21 (165) and 22 (159) were higher. Now, cycle 23 was low (122), so cycles 24 and 25 are expected to be higher. By how much, it is not possible to say, but cycles 24 and 25 should certainly be larger than cycle 23, which was 122. So, Ahluwalia's estimate for cycle 25 will be larger than the estimates of 70 – 110 for cycle 25 given by some other workers (Hathaway and Wilson, 2004; Du, Wang, and He, 2006). Thus, different approaches lead to different expectations, and some of these are likely to prove erroneous. Let us wait and see. It may be remembered that for cycle 23 also, predictions were in a very wide range ∼80 – 210, and from 20 predictions, only 8 were near the observed value 122 within ±20. [See the critical assessment of cycle 23 in Kane, 2001.]

Recently, Cameron and Schüssler (2007) studied the origin of the predictive skill of some methods to forecast the strength of solar activity cycles. They mention that since stronger cycles tend to rise faster to their maximum activity (known as the Waldmeier effect), the temporal overlapping of cycles leads to a shift of the minimum epochs that depends on the strength of the following cycle. This information is picked up by precursor methods and also by the flux-transport model with a schematic source. Therefore, their predictive skill does not require a memory (*i.e.*, a physical connection between the surface manifestations of subsequent activity cycles).

In this paper and in all others mentioned here, the solar activity is represented by sunspot numbers. However, it is good to remember that sunspots as such (or for that matter even the 2800-MHz solar radio flux) have no direct connection with interplanetary space and/or the terrestrial environment. The effects come through solar emissions (total solar irradiance, UV, EUV, and X-ray fluxes, coronal mass ejections, open magnetic fluxes, *etc.*) and these have solar cycle variations only roughly parallel to sunspot number, and in one case, not even that. (Geomagnetic activity has generally two peaks, one near sunspot maximum and another in the declining phase of sunspot activity, the latter peak being mainly due to high-speed solar wind streams emanating from coronal holes.) Thus, high or low solar activity as judged from sunspot numbers, even if correctly predicted, may not have any clear resemblance (certainly not one-to-one) with terrestrial features such as thermospheric temperatures, which are important for satellite drags. The dissimilarity between sunspot variations (including the occurrence of more than one peak, with Gnevyshev peaks and the in-between Gnevyshev gaps seen during a 2 – 3 year interval of maximum sunspot activity) and the variations of solar emissions is illustrated in detail in Kane (2006a, 2006b). The TSI (Total Solar Irradiance) is the lifeline of terrestrial life, but it has a very small solar cycle variation (1%, justifying the term "Solar Constant"). Nonetheless, TSI reaching the surface of the Earth (Kane, 2005) is greatly modified by cloud coverage, which is highly localized and can have variations of several tens of percent from hour to hour or several percent from day to day and is different in different localities.

The *global* cloud cover is reported to have a solar cycle variation (Marsh and Svensmark, 2000), but its amplitude is only ∼2 – 3%. Solar UV and EUV have solar cycle variations of a few ten percent (almost parallel to sunspots) and these are reflected qualitatively in terrestrial ionosphere and thermospheric temperature and density (Marcos *et al.*, 2005), but quantitative comparison is uncertain as reliable data are available for only two recent cycles (22 and 23). In the stratosphere, ozone and temperature have a solar cycle dependence of a few percent, but a major part of the variations is a QBO (quasi-biennial oscillation) unrelated to solar activity (Hood, 2004; Lastovicka, 2005). The same is true of 30-mbar geopotential heights in the polar regions (Labitze, 2005). Regarding climate (confined to the troposphere), a relationship with solar activity seems to be, to say the least, dubious, mainly because of the interference of anthropogenic causes and natural phenomena unrelated to solar activity such as El Niño/Southern Oscillation, volcanoes, *etc.* (Lastovicka, 2005; Moore, Grinsted, and Jevrejeva, 2006). Hence, even if Rz(max) is predicted accurately, the information will be of limited value.

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