DID PREDICTIONS OF THE MAXIMUM SUNSPOT NUMBER FOR SOLAR CYCLE NO. 22 COME TRUE?

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Abstract. Solar cycle No. 22 which started in 1986 seems to have already passed through a maximum. The maximum annual mean sunspot number was 157 for 1989. The maximum twelve-month running average was 159, centered on July 1989. For cycle 21, the similar value was 165 centered at December 1979. Thus, cycle 22 is slightly *weaker* than cycle 21. Schatten and Sofia (1987) had predicted a stronger cycle 22 (170 ± 25) as compared to cycle 21 (140 ± 20). Predictions based on single variable analysis, viz., R_z(max) versus *aa*(min) were ~ 165 and came true. Predictions based on a bivariate analysis, viz., R_z(max) versus *aa*(min) and R_z(min) were ~ 130 and proved to be underestimates. Other techniques gave over- or underestimates.

1. Introduction

Solar activity affects the density and temperature of the thermosphere which, in turn, affects the lifetimes of low altitude satellites. As such, there is great interest in knowing beforehand the likely level of maximum solar activity in a solar cycle. Several types of prediction schemes have been used in the past. Some are based on 'statistical', 'secular variations', or 'sunspot periodicity' models (see Kane and Trivedi, 1985, and references therein; also Brown, 1986), and are not found to be very useful for accurate, reliable predictions. Others use geomagnetic indicators at solar minimum as precursors for the coming solar maximum (Ohl, 1966, 1968, 1976; Brown and Williams, 1969; Sargent, 1977, 1978; Kane, 1978, 1987a, b, 1989; Simon and Legrand, 1986; Gonzalez and Schatten, 1987; Wilson, 1988b, c, d, e; Brown, 1988; Butcher, 1990). The physical basis for these geomagnetic precursor methods is that the geomagnetic activity is affected by the extended solar field (interplanetary field, Schatten and Wilcox, 1967). The geomagnetic field at solar minimum reflects the Sun's polar field via the solar wind (see also Simon and Legrand, 1989). Schatten *et al.* (1978) proposed the hypothesis that solar *polar* flux, wound by differential rotation into a subsurface toroidal flux, emerges as the next cycle's sunspots. Hence, the strength of the polar magnetic field at sunspot minimum could be a precursor of the strength of the next cycle's sunspot activity. They employed four different ways of estimating the Sun's polar magnetic field near solar minimum and estimated the sunspot number at the maximum of solar cycle No. 21 (1975–1986) as 140 ± 20, which proved to be an underestimate compared to the observed value of ~ 160. For the recent solar cycle No. 22 which started in 1986, Schatten and Sofia (1987) used the same 'dynamo theory' method of Schatten *et al.* (1978) and predicted a maximum sunspot number of 170 ± 25 to occur in September 1990 ± 1 year. For the same cycle No. 22, Wilson (1988b) used the method of bilinear fit where R_z(max) (annual mean) was correlated with R_z(min) and *aa*(min) and predicted

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a maximum sunspot number of 92 ± 19 (equivalent to 96 ± 20 for the smoothed sunspot number). However, in a revised analysis, Wilson (1988e) gave the values for R_M (smoothed maximum sunspot number) as 164 ± 40 for the single variable analysis and 144 ± 20 for the bivariate analysis while Kane (1989), using the same type of analysis, predicted 165 ± 35 for single variable correlation, i.e., R_z(max) versus *aa*(min) only and ~ 133 for a bivariate fit. Since 1986, several years have passed and solar cycle No. 22 has probably gone through a maximum already. In this note, we check which predictions came true.

2. Data

Figure 1 shows a plot of the monthly mean sunspot numbers (top plot) for solar cycle No. 21 (1975–1986) and solar cycle No. 22 (1986 onwards). The month to month fluctuations are very large and maxima are difficult to locate. Hence, only running means over 12 consecutive months are usually employed in statistical analysis. To get the centering correct, an arithmetic average of two sequential 12 month running means of

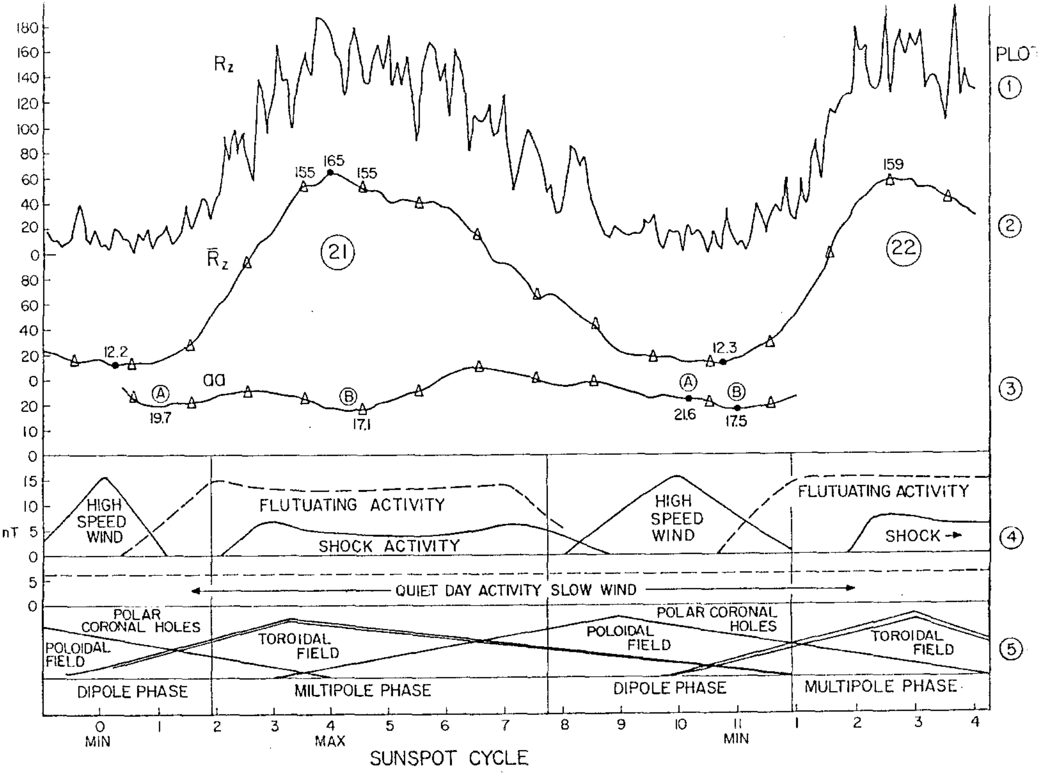

Fig. 1. Plot 1, monthly mean sunspot number R_z. Plot 2, 12-month running averages of R_z: the triangles represent annual (January–December) means. Plot 3, smoothed geomagnetic *aa* index; both cycles 21 and 22 had two *aa* minima, *A* and *B*. Plot 4, intervals when four types of geomagnetic activity occur (slow wind, high speed wind, shock activity, fluctuating activity). Plot 5, intervals when solar poloidal (dipole) and toroidal fields occur.

monthly mean numbers is obtained and is termed the 'smoothed monthly mean sunspot number'. Values are given in McKinnon (1987). Recent values are in *Solar Geophysical Data*, USA, Department of Commerce. In Figure 1 the second plot shows these smoothed values. The third plot in Figure 1 shows the geomagnetic *aa* indices (Mayaud, 1973; and *Solar Geophysical Data*), smoothed in the same manner. Only values near sunspot minima are shown. For prediction, Kane (1989) used the expression

$$R_z(\max) = (9.5 \pm 1.9)aa(\min) + (3.9 \pm 21.4) \tag{1}$$

for a single variable relationship and the expression

$$R_z\max) = (12.2 \pm 1.4)aa(\min) - (7.3 \pm 2.1)R_z(\min) + (6.2 \pm 13.6) \tag{2}$$

for a bivariate relationship. For cycle No. 21, an $aa(\min) = 19.8$ occurred in 1977 and, using the same in a single variable analysis, Kane (1987a) reported a prediction $R_z(\max)$ 183 ± 40, which turned out to be higher than the observed values $R_z(\max) = 155$ for 1979. However, as shown in Kane (1987b), there was a second minimum, viz., $aa(\min) = 17.5$ in 1980 which would have given a prediction $R_z(\max) = 165 \pm 35$, very near the observed value 165. Thus, for cycle 21, the single variable analysis gave an accurate prediction. A bivariate analysis would have given $R_z(\max) = \sim 135$, much below the observed value. Schatten *et al.* (1978) predicted $R_z(\max) = 140 \pm 20$, which turned out to be *lower* than the observed value 165.

For cycle 22, it is interesting to note that the input values are almost the same as for cycle 21. Thus, for cycle 21, $aa(\min) = 17.1$, $R_z(\min) = 12.2$, whereas for cycle 22, $aa(\min) = 17.5$, $R_z(\min) = 12.3$. Hence, the $R_z(\max)$ for both the cycles was expected to be almost equal. This is what happened. The observed values were 165 for cycle 21 and 159 for cycle 22. These values match the predictions from Equation (1). From Equation (2), the expected values would be ~ 135. Thus, for cycle 22, our single variable formulation gave a better prediction. Obviously, Wilson's (1988b) prediction of 96 ± 19 for cycle 22, based on a bivariate analysis, turned out to be an underestimate. For a single variable analysis, Wilson's formula would have given ~ 135 for $aa(\min) = 15.3$ used by him and ~ 150 for $aa(\min) = 17.5$, while Gonzalez and Schatten (1987) predicted 163 ± 40 for October 1990. Schatten and Sofia (1987) predicted 170 ± 25, which is larger than the observed value 159. Thus, the 'dynamo theory' method of Schatten *et al.* (1978) gave an overestimate for cycle 22 and an underestimate for cycle 21. In particular, their claim that cycle 22 (their estimate 170 ± 25) would be stronger than cycle 21 (their estimate 140 ± 20) did not turn out to be correct, as the observed values were 159 and 165 for cycles 22 and 21, respectively. If anything, cycle 22 turned out to be slightly *weaker* than cycle 21. Table I summarizes various predictions.

It is strange that the predictions based on a bivariate analysis turned out to be *underestimates* for cycle 22. Wilson (1988b) reported correlation coefficients of 0.891 and 0.982, and Kane (1989) reported 0.889 and 0.965 for the single variable (Equation (1) type) and bivariate (Equation (2) type) formulations, respectively. Thus, the bivariate formulation was expected to give a better fit. In Equations (1) and (2) based on cycles 12–20 only, inserting the values of $aa(\min)$ and $R_z(\min)$ on the right-hand side

TABLE I

Comparison of observed and predicted values of double-smoothed R_z(max) for solar cycles 21 and 22

	Solar cycle 21	Solar cycle 22
	aa(min) = 19.7, (21*A*), Dec. 1976 *aa*(min) = 17.1, (21*B*), Apr. 1980 R_z(min) = 12.2 Mar. 1976	*aa*(min) = 21.6, (22*A*), Feb. 1986 *aa*(min) = 17.5, (22*B*), Dec. 1986 R_z(min) = 12.3 Sep. 1986
Observed R_z(max):		
(a) 12-month running average	165 Dec. 1979	159 July 1989
(b) Annual mean	155 (1979), 155 (1980)	157 (1989)
Predicted R_z(max):		
(a) Single variable:		
Lantos and Simon (1987)		115 ± 20
Gonzalez and Schatten (1987)		163 ± 40 (Oct. 1990 ± 9 mon)
Wilson (1988e)		164 ± 20 for *aa*(min)
		154 ± 35 for R_z(min)
Kane (1989)	190 ± 40 (21*A*)	208 ± 40 (22*A*)
	166 ± 35 (21*B*)	170 ± 35 (22*B*). Early 1989
Ohl (1976)	160 ± 20	
(b) Bivariate analysis:		
Sargent (1977, 1978)	156	$\sim$120
Wilson (1988c)		145 ± 4 for *Ap*(min), R_z(min)
Wilson (1988e)		144 ± 10 for *aa*(min), R_z(min)
Wilson (1988d)		75 ± 25 for other variables
Kane (1989)	$\sim$156 (21*A*)	$\sim$179 (22*A*)
	$\sim$125 (21*B*)	$\sim$129 (22*B*)
Thompson (1987)		159 (?)
(c) Other techniques:		
Schatten *et al.* (1978)	140 ± 20 (Dec. 1979 ± $\frac{1}{2}$ year)	
Schatten and Sofia (1987)		170 ± 25 (Sep. 1990 ± 1 year)
Brown and Butcher (1981)	167 ± 9	
Butcher (1990)		187 ± 36
Brown (1988)	155 ± 31	174 ± 35
Statistical		
Wilson (1984, 1988d)		107 and 75
Brown and Simon (1986)		90
Secular		
Wilson (1988e)		78
Brown and Ximon (1986)		106
McNish and Lincoln (1949)		198 ± 52 (Feb. 1990)
NOAA/NESDIS (1989)		
Koons and Gorney (1990)		$\sim$194 ± 26

would give the *expected* values of R_z(max). Figure 2 shows a plot of observed versus expected values for the single variable formulation in Figure 2(a) and for the bivariate formulation in Figure 2(b). For cycle 21 and 22, *A* and *B* refer to the first and second minima for *aa* (marked on the third plot of Figure 1). In both the cases, the latter minima (*B*) are lower. However, as pointed out in Kane (1989), there was a curious complication

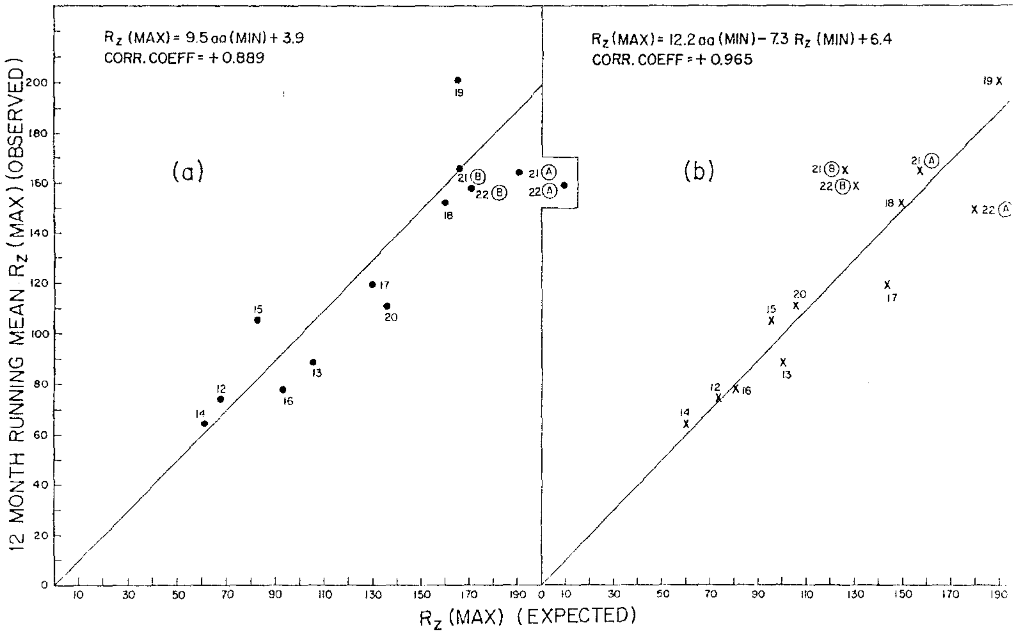

Fig. 2. Plots of R_z(max) observed versus R_z(max) expected for (a) single variable formulation, viz., R_z(max) versus *aa*(min) and (b) a bivariate formulation, viz., R_z(max) versus *aa*(min) and R_z(min). For cycles 21 and 22, (21*A*, 21*B*) and (22*A*, 22*B*) refer to the two *aa* minima for each cycle (see Figure 1).

for cycle 21. In Figure 2(a), 21*B* fits better than 21*A*. But the minimum 21*B* occurred in 1980, almost near the sunspot *maximum* (see Figure 1, plot 3) and could not serve as a precursor. If, instead, 21*A* is considered relevant, then the fit is better for the bivariate formulation (Figure 2(b)) than for the single variable formulation (Figure 2(a)). For cycle 22 also, there were two *aa* minima. Amongst these, 22*B* (17.5) is lower than 22*A* (21.6). However, if 22*B* is used, the fit is better in Figure 2(a) than in 2(b). If 22*A* is used, the fit is bad in both Figure 2(a) and Figure 2(b). Hence, 22*A* is definitely to be discarded. But 22*B* favours the single variable formulation rather than the bivariate formulation. Thus, whereas the bivariate formulation was superior to the single variable formulation for cycles 12–20, cycles 21 and 22 seem to favour the single variable formulation, in a complicated way.

3. Physical Basis

For practical purposes, regressions like those shown in Figure 2, based on geomagnetic activity at sunspot minimum, seem to be fairly good predictors, better than anything else we know, certainly as good as Schatten and Sofia's (1987) predictions, which are based on a plausible physical model. Recently, Layden *et al.* (1991) have reviewed in detail a general framework for forecasting the amplitude of the solar cycle, based on a simple understanding of the solar dynamo, which requires knowledge of the Sun's polar magnetic field strength at the preceding activity minimum. For cycle 22, their predictions of maximum R_z using various parameters were as follows:

Basic parameter	Predicted R_z(max)
Polar field bending angle	(768 ± 10155)
Coronal hole size	(923 ± 60)
Isophote flattening	(49 ± 317)
Number of polar faculae	Not available
Interplanetary magnetic field	279 ± 626
Geomagnetic *aa* index	160 ± 28
Geomagnetic *Ap* index	162 ± 43
aa index (Svalgaard, 1977)	182 ± 26
Sun's polar magnetic field maximum	<(190 – 215)
Final	171 ± 26

As can be seen, the only worthwhile predictions are those based on geomagnetic activity indices.

Geomagnetic activity can be caused by a variety of interplanetary phenomena. Legrand and Simon (1989) have classified geomagnetic phenomena into two distinct classes, viz., those due to shock events and those due to solar wind stream activity. The *aa* indices are known to be highly correlated with solar wind velocity and, the wind streams can be further subdivided into three categories, viz., slow wind, the high speed wind and the fluctuating velocity wind. The shock events and the 3 categories of wind stream activity are *not distributed randomly* during the solar cycle. They have fairly definite but different phase relationships with the sunspot cycle, as illustrated in the 4th plot of our Figure 1. Whereas shock activity and fluctuating velocity wind activity are strong near sunspot maximum, the high speed wind stream activity is *large near and immediately before the sunspot minimum.* In Simon and Legrand (1989), the *solar sources* of these various categories of geomagnetic activity are explored and their links with the sunspot cycle are investigated. The spatial distribution of solar wind velocity in the interplanetary medium seems to be linked with two 'key parameters' of the solar *poloidal* field, viz., the intensity of the solar dipole and the thickness of the slow wind sheet in the solar equatorial plane. The dipole reaches its peak intensity *a few years before sunspot minimum* (see plot 5 in our Figure 1). In the next few years, the polar field fades away and, by differential rotation of the Sun, is transformed into a toroidal field, which gives rise to subsequent sunspots and solar activity. During the rising phase of the sunspot cycle, multipoles are formed and reach maximum soon after the sunspot maximum. Soon after, the multipoles disappear, and a *reversal* of the solar dipole occurs, and a new reverse poloidal field is born and develops. In the solar ecliptic plane, the distribution of the solar wind velocity depends upon the shape and the thickness of the slow wind sheet. Thus, the solar wind characteristics and the consequent geomagnetic activity originate from the *cyclic* behaviour of the *poloidal* field topology. The maximum of the sunspot activity is related to the *maximum intensity of the solar dipole, reached 5* *or 6 years earlier*, i.e., ~0–2 years before the sunspot minimum. At sunspot minimum, when all other activities (shock activity, fluctuating activity) are negligible, the geomagnetic activity would be mainly due to high-speed wind streams. These streams originate in polar *coronal holes* (Simon, 1979), which are regions of low density in the corona, with unipolar magnetic fields of an open configuration. These polar coronal holes seem to be intimately related to the poloidal dipole field. For several years near the sunspot minimum, two large coronal holes of opposite polarity are present over the solar polar regions, covering as much as 25% of the solar surface (see Bravo and Otaola, 1989). As the sunspot cycle progresses towards the maximum, the polar holes shrink, reaching their smallest size around sunspot maximum and may even disappear. Soon after, the polar field reversal occurs and the reversed poles develop rapidly during the declining phase of the sunspot cycle. Later, this poloidal dipole field gets destroyed and emerges as a toroidal field giving birth to the next sunspot cycle, the strength of which is proportional to the strength of the earlier poloidal field.

It is obvious, therefore, that *any* measure of the poloidal field would, in principle, be a precursor of the strength of the forthcoming sunspot cycle. Schatten *et al.* (1978) estimated the strength of the Sun's polar magnetic field near sunspot minimum in four different ways. From the shape of the corona at eclipses, one could estimate (1) the coronal flattening (Lundendorf index, Billings, 1966) or (2) the bending of high latitude plumes. Also, estimates could come from (3) the flattening of the 'warped current sheet' in interplanetary space and (4) counting the numbers of faculae at the solar poles. For cycle 21, the four methods gave four estimates of R_z(max) as 155 ± 25, 125 ± 15, 135 ± 20, and 140 ± 20, yielding an average of 140 ± 20. The uncertainly ± 20 in the average was retained as the four methods were not completely independent. Using the same method, Schatten and Sofia (1987) predicted 170 ± 25 for cycle 22. Strictly speaking, 140 ± 20 and 170 ± 25 are not statistically significantly different. Hence, one could get away by claiming that cycle 21 and cycle 22 were expected to have *similar* R_z(max), in agreement with the observed similar values 165 and 159, respectively. However, Schatten and Sofia (1987) referred to their 170 ± 25 as a *large* sunspot number and mentioned specifically that 'the next solar cycle (22) will be an exceptionally active one, somewhat larger than the last (21)'. To us, this prediction does not seem to have come true and probably indicated the limitation of this fundamental approach adopted by them. Since there is a close link between the evolution of coronal holes and the evolution of the Sun's general magnetic field (Webb, Davis, and McIntosh, 1984), a good correlation between the polar coronal hole size near sunspot minimum and the succeeding R_z(max) would be expected. Bravo and Otaola (1989) explored this possibility and obtained a correlation coefficient of −0.83 which turned to +0.89 with a lag of ~76 months (6.3 years). Thus, R_z variations seemed to *follow* the polar coronal hole area with a lag of ~6 years. Since the coronal hole minimum occurred in 1980, sunspot minima should occur in 1986, which came true. However, Bravo and Otaola (1989) could not get the *polar* coronal hole data for 1986 and hence could not predict the R_z(max) for cycle 22. Thus, this methodology seems to be difficult to adopt. In that case, our methodology of using *aa* indices at sunspot minimum seems to be the most useful.

For cycles 12–20, the correlation between R_z(max) and *aa*(min) was excellent (+ 0.89). For R_z(max) versus *aa*(min) and R_z(min) the correlation was still better (+ 0.97). However, for cycles 21 and 22, there were complications in the form of two *aa* minima (*A* and *B*), the *A*s favouring the bivariate formulation and the *B*s favouring the single variable formulation. The *B*s were deeper and hence more appropriate; but, for cycle 21, *B* occurred too late to be useful for prediction. This methodology was initiated by Ohl (1966, 1968, 1976) who showed that the level of geomagnetic activity (K_p index) in the descending branch of a solar cycle was well correlated with the height of the following cycle and predicted R_z(max) = 140–180 for cycle 21. Sargent (1977, 1978) used the bivariate expression

$$R_{\max(n+1)} = 3.91 + 8.56\,(X_1 - 0.92X_2)\,, \tag{3}$$

where X_1 is the average value for monthly mean *aa* indices for the 36 months preceding $R_{\min(n)}$ and $X_2 = R_{\min(n)}$. Sargent's prediction for cycle 21 was 156. For cycle 22, his prediction would have been ~ 120, a gross underestimate (see Table I).

Besides the *aa* analysis, another type of analysis using parameters at sunspot minimum is that of Brown and Williams (1969) who showed that on some quiet days, the normal pattern of geomagnetic *H* variation, $S_q(H)$, at temperate latitudes (~ 50° N) is abnormal. The number of such Abnormal Quiet Days (AQD) has a solar cycle variation. Also, the number of AQD during sunspot minimum is a precursor of the strength of the forthcoming R_z(max). Using such a relationship, Brown (1988) predicted 155 ± 31 for cycle 21 and 175 ± 35 for cycle 22 (see Table I). Butcher (1990) predicted 187 ± 36 for cycle 22. Withbroe (1989) recently reviewed solar cycle predictions for cycle 22 by three broad techniques, viz., statistical, precursor and McNish and Lincoln (1949) and gave the values ~ 94, 154, and 191, respectively (see Table I). The McNish and Lincoln (1949) technique is a 'self-correcting' technique which relates sunspot number at *N* months after sunspot minimum to the mean for that month from preceding cycles and a correlation term related to the departure of the current cycle from this mean. Recently, Koons and Gorney (1990) have used a precursor technique in a novel way. A *neural* network using a back propagation algorithm is trained to recognize a pattern in the onset of a new sunspot cycle that can be used to predict R_z(max) as well as the number of months from sunspot minimum to maximum. They predicted R_z(max) = 194 ± 26 to occur 42 months (March 1990) from sunspot minimum. Wilson (1988a) also made a similar attempt but considered it too early to predict cycle 22 accurately.

4. Conclusions

There is good reason to believe that the solar poloidal (dipole) field is a key parameter guiding the solar cycle and the strength of the dipole, though varying from cycle to cycle, is related to the strength of the sunspot maximum occurring ~ 6 years later. Thus, estimates of the solar polar magnetic field at or before the sunspot minimum could be useful for predicting the intensity of the next sunspot cycle. Attempts at estimating the solar polar magnetic field so far yielded R_z(max) predictions with an accuracy of ~ ± 30.

The indirect method of using *aa* indices at sunspot minimum as an indicator of the solar polar field is simpler and yields predictions with an accuracy of roughly the *same* order. In the latter case, two types of analyses are possible, viz., single variable analysis with R_z(max) versus *aa*(min) only, and bivariate analysis with R_z(max) versus *aa*(min) and R_z(min). For cycles 12–20, the bivariate analysis gave more accurate predictions. But, for cycles 21 and 22, the choice between the two types of analyses was somewhat ambiguous, mainly because of the complex nature of *aa*(min) (having two minima) during the sunspot minimum periods. Which of the two would be more appropriate for cycle 23 (year 2000!) is anybody's guess! The role of $R_{\min}$ in the prediction schemes is not quite clear. A direct correlation between R_z(min) and R_z(max) is only + 0.27 (Kane, 1978) but R_z(max) correlates well with R_z(min) for helio latitudes 20°–40° (Kane and Trivedi, 1980). As shown by Bravo and Otaola (1989), the temporal evolution of R_z, including R_z(min), may be intimately related to the evolution of the size of polar coronal holes and hence to the evolution of the solar poloidal (dipole) field, even on a short time scale (1 year or less), about 6 years earlier.

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References

Billings, D. E.: 1966, *A Guide to the Solar Corona*, Academic Press, New York, p. 226.

Bravo, S. and Otaola, J. A.: 1989, *Solar Phys.* **122**, 335.

Brown, G. M.: 1986, in P. A. Simon, G. Heckman, and M. A. Shea (eds.), 'Long-Term Solar Activity Predictions', *Solar-Terrestrial Predictions*, NOAA, Boulder, CO, p. 1.

Brown, G. M.: 1988, *Nature* **333**, 121.

Brown, G. M. and Butcher, E. C.: 1981, *Planetary Space Sci.* **29**, 73.

Brown, G. M. and Simon, P. A.: 1986, in P. A. Simon, G. Heckman, and M. A. Shea (eds.), 'Long-Term Solar Activity Predictions', *Solar-Terrestrial Predictions*, NOAA, Boulder, CO, pp. 1–7.

Brown, G. M. and Williams, W. R.: 1969, *Planetary Space Sci.* **17**, 455.

Butcher, E. C.: 1990, *Geophys. Res. Letters* **17**, 117.

Gonzalez, G. and Schatten, K. H.: 1987, *Solar Phys.* **114**, 189.

Kane, R. P.: 1978, *Nature* **274**, 139.

Kane, R. P.: 1987a, *Solar Phys.* **108**, 415.

Kane, R. P.: 1987b, *Solar Phys.* **114**, 194.

Kane, R. P.: 1989, *Solar Phys.* **122**, 175.

Kane, R. P. and Trivedi, N. B.: 1980, *Solar Phys.* **68**, 135.

Kane, R. P. and Trivedi, N. B.: 1985, *J. Geomag. Geoelect.* **37**, 1071.

Koons, H. C. and Gorney, D. J.: 1990, *EOS, Trans. AGU*, **71**, 677.

Lantos, P. and Simon, P.: 1987, 'Prediction of the Next Solar Activity Cycle', *Proc. 8th ESA Symp. on European Rocket and Balloon Programs and Related Research*, European Space gency, Noordwijk, SP-270, pp. 451–453.

Layden, A. C., Fox, P. A., Howard, J. M., Sarajedini, A., Schatten, K. H., and Sofia, S.: 1991, *Solar Phys.* **132**, 1.

Legrand, J. P. and Simon, P. A.: 1989, *Ann. Geophys.* 7(6), 565.

Mayaud, P. N.: 1973, 'A Hundred Year Series of Geomagnetic Data 1868–1967', *Indices aa, Storm Sudden Commencements*, IAGA Bulletin No. 33, IUGG Publication Office, Paris.

McKinnon, J. A.: 1987, *Sunspot numbers: 1610 :1985*, Report UAG-95 WDC-A for Solar-Terrestrial Physics, NOAA, Boulder, CO, January, pp. 112.

McNish, A. G. and Lincoln, J. V.: 1949, *EOS, Trans. AGU* **30**, 673.

NOAA/NESDIS: 1989, *Solar-Geophysical Data, 1989*, Solar-Geophysical Data Prompt Reports January 1989 No. 533, National Environmental Satellite, Data and Information Service, NOAA, Boulder, CO.

Ohl, A. I.: 1966, *Soln. Dann.* No. 12, 84.

Ohl, A. I.: 1968, 'Forecast of the Maximum Wolf Number for the Current Eleven-Year Cycle', *Problems of the Arctic and Antarctic*, No. 22, pp. 137–139.

Ohl, A. I.: 1976, *Soln. Dann.* No. 9, 73.

Sargent, H. H. III: 1977, *EOS, Trans. AGU* **58**, 1220.

Sargent, H. H. III: 1978, 'A Prediction for the Next Sunspot Cycle', *Proc. 28th IEEE Vehicular Technical Conf.*, Denver 1978, pp. 490–496.

Schatten, K. H. and Sofia, S.: 1987, *Geophys. Res. Letters* **14**, 632.

Schatten, K. H. and Wilcox, J. M.: 1967, *J. Geophys. Res.* **72**, 19.

Schatten, K. H. Scherrer, P. H., Svalgaard, L., and Wilcox, J. M.: 1978, *Geophys. Res. Letters* **5**, 411.

Simon, P. A.: 1979, *Solar Phys.* **63**, 399.

Simon, P. A. and Legrand, J. P.: 1986, *Astron. Astrophys.* **155**, 227.

Simon, P. A. and Legrand, J. P.: 1989, *Ann. Geophys.* 7(6), 579.

Svalgaard, L.: 1977, in J. Zirker (ed.), *Coronal Holes and High Speed Wind Streams*, Colorado Associated University Press, Boulder, p. 371.

Thompson, R. J.: 1987, *Solar Geophysical Data September 1987 (November 517)*, Preliminary Report and Forecast of Solar-Geophysical Data, NOAA, Space Environmental Res. Lab. Boulder CO, SESC PRF 626, p. 12.

Webb, D. B., Davis, J. M. and McIntosh, P. S.: 1984, *Solar Phys.* **92**, 109.

Wison, R. M.: 1984, *A Comparative Look at Sunspot Cycles*, NASA Tech. Paper 2325, Marshall Space Flight Center, Alabama.

Wilson, R. M.: 1988a, *Solar Phys.* **117**, 179.

Wilson, R. M.: 1988b, *Geophys. Res. Letters* **15**, 125.

Wilson, R. M.: 1988c, *Nature* **335**, 773.

Wilson, R. M.: 1988d, *Solar Phys.* **115**, 397.

Wilson, R. M.: 1988e, *J. Geophys. Res.* **93**, 10011.

Withbroe, G. L.: 1989, *J. Spacecraft Rockets* **26**, 394.