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Gauging the Nearness and Size of Cycle Minimum

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TECHNICAL PAPER

GAUGING THE NEARNESS AND SIZE OF CYCLE MINIMUM

I. INTRODUCTION

Conventionally, a sunspot cycle is described in terms of the 12-month moving average of monthly mean sunspot number, or smoothed sunspot number as it is more commonly known, which is used to reduce the effect of random movements on the time series data and, in particular, to remove seasonal movements in the data.[1,2] The minimum value of the 12-month moving average is called "minimum amplitude," and its occurrence is the basis for determining when a new cycle begins and when the old cycle ends, thereby, yielding the "period" of the old cycle. Likewise, the maximum value of the 12-month moving average is called "maximum amplitude," and its occurrence, together with that of minimum amplitude, is the basis for determining the "ascent" and "descent" durations of a sunspot cycle. Wilson et al.[3] have tabulated the values and occurrence dates, or epochs, of minimum and maximum amplitude for sunspot cycles 0–22, spanning the years 1750 to the present.

Cycle 22, which in terms of the 12-month moving average began in September 1986 and peaked in July 1989, is now well into decline and is rapidly approaching its end; hence, conventional onset for cycle 23 appears imminent. In fact, the first high-latitude (i.e., $\geq 25°$) spots of new cycle 23 have already begun to appear (first in May 1996[4]), and the late behavior of cycle 22 continues to strongly suggest that it will be of short period, having a length shorter than 11 years.[4–7] Because of the importance of minimum amplitude in cycle prediction,[4,8,9] and the seemingly imminent onset of cycle 23, as well as the start of the construction phase for the *International Space Station,*[10] it is imperative that one determines, as quickly and as accurately as possible, the expected size and placement (i.e., timing) of minimum amplitude for cycle 23.[7,8]

While the 12-month moving average of monthly mean sunspot number ably serves as the chief descriptor of the sunspot cycle, it does have certain drawbacks, especially near cycle minimum. These include, in particular, a general lack of timeliness (i.e., specific knowledge of the 12-month moving average always lags real time by at least 6 months) and a slowness of response (i.e., the 12-month moving average, on occasion, either has changed little for several consecutive months near minimum or has shown considerable variation near minimum, rising ever so slightly, only to fall again a few months later). Thus, one generally cannot be certain as to the value and placement of minimum amplitude until, often, about a year or so into the new cycle. In the hope that one can reduce this ambiguity, we examine moving averages of shorter length (2-, 4-, and 6-month), together with the behavior of monthly mean sunspot number and other cycle-related behavior (e.g., the Mg II index), to determine how well we can gauge the nearness and size of minimum amplitude; in particular, for cycle 23.

II. MOVING AVERAGE FORMULAE

Table 1 identifies the moving averages that will be employed in this study. These include the 2-, 4-, 6-, and 12-month moving averages of monthly mean sunspot number (sometimes, these particular averages are also referred to as the 3-, 5-, 7-, and 13-month running mean). Only even-numbered moving averages are employed so that the computed value corresponds to a particular month. In the formulation, the numbers in parentheses on the right side of the equation correspond to individual months before (negative number) or after (positive number) the month of interest (numbered 0), and R refers to monthly mean sunspot number. For longer length moving averages, the $R(0)$ term is replaced by the summation operation over an interval of individual monthly values (denoted by the index term i) centered on the month of interest (0), and the denominator is always twice the size of the moving-average length.

TABLE 1.—*Formulae for selected moving averages.*

Moving Average	Computational Formula
2-Month	$R(2\text{-mo}) = \dfrac{R(-1) + R(+1) + 2R(0)}{4}$
4-Month	$R(4\text{-mo}) = \dfrac{R(-2) + R(+2) + 2\sum_{-1}^{+1} R(i)}{8}$
6-Month	$R(6\text{-mo}) = \dfrac{R(-3) + R(+3) + 2\sum_{-2}^{+2} R(i)}{12}$
12-Month	$R(12\text{-mo}) = \dfrac{R(-6) + R(+6) + 2\sum_{-5}^{+5} R(i)}{24}$

III. RESULTS

Table 2 gives the minimum values of the 2-, 4-, and 6-month moving averages, as well as the minimum value of monthly mean sunspot number *R*, obtained within 12 months of minimum amplitude occurrence for the modern era sunspot cycles 10–22 (so-named because they are the most reliably known sunspot cycles[11]). In table 2, the minimum amplitude, denoted here as *Rm*, is also given (recall that the minimum value of the 12-month moving average is, by definition, the minimum amplitude). From table 2, one finds that the minimum amplitude for a modern era sunspot cycle has ranged between 1.5 and 12.3 (having a mean of 5.7 and a standard deviation of 3.7). For monthly mean sunspot number *R*, its minimum value has ranged between 0.0 and 3.1 (having a mean of 0.6 and a standard deviation of 0.9), while for the 2-, 4-, and 6-month moving averages, their minimum values have ranged, respectively, between 0.2 and 7.5 (having both a mean and standard deviation of 2.6); 0.5 and 10.2 (having a mean of 3.7 and a standard deviation of 2.9); and 0.6 and 11.1 (having a mean of 4.1 and a standard deviation of 3.1).

TABLE 2.—*Minimum values for selected parameters.*

Cycle	*Rm*	*E*(*m*)	*R*	*R*(2-mo)	*R*(4-mo)	*R*(6-mo)
10	3.2	Dec. 1855	0.0	1.7	2.7	2.7
11	5.2	Mar. 1867	0.0	0.6	2.8	3.2
12	2.2	Dec. 1878	0.0	0.6	1.0	1.6
13	5.0	Mar. 1890	0.2	2.3	3.1	3.6
14	2.6	Jan. 1902	0.0	0.8	1.6	2.0
15	1.5	Aug. 1913	0.0	0.2	0.5	0.6
16	5.6	Aug. 1923	0.5	2.2	3.6	4.4
17	3.4	Sept. 1933	0.2	1.1	2.0	2.1
18	7.7	Feb. 1944	0.3	2.6	4.0	3.9
19	3.4	Apr. 1954	0.2	0.9	2.2	2.6
20	9.6	Oct. 1964	3.1	6.1	6.2	6.8
21	12.2	June 1976	1.9	7.1	10.2	11.1
22	12.3	Sept. 1986	1.1	7.5	8.6	9.0
Mean	5.7		0.6	2.6	3.7	4.1
Standard Deviation	3.7		0.9	2.6	2.9	3.1

Note: *E*(*m*) is the epoch of smoothed sunspot number minimum (i.e., the occurrence date of minimum amplitude *Rm*).

Table 3 gives the relative placement of the minimum value of the monthly mean and the various moving averages with respect to minimum amplitude occurrence, where negative values mean that it occurred so many months before minimum amplitude occurrence and positive values mean that it occurred so many months after minimum amplitude occurrence. For the various moving averages, a single minimum is noted to have occurred at the elapsed time given; however, for *R* the minimum value was sometimes seen on more than one occasion during the ±12-month interval about minimum amplitude occurrence. For example, cycle 14 had a minimum monthly mean sunspot number of 0.0 (see tables 2 and 3) at elapsed times –9, –1, +1, and +3 months relative to *Rm* occurrence. For *R*, its minimum value is found to have always bound minimum amplitude occurrence by –9 to +5 months (more typically, –4 to +5 months). For the 2- and 4-month moving averages, their minimum values are found to have always bound minimum amplitude occurrence by –5 to +5 months, and for the 6-month moving average by –6 to +3 months (more typically, –3 to +3 months).

TABLE 3.—*Elapsed time (months) of minimum values from* Rm *occurrence.*

Cycle	*R*	*R*(2-mo)	*R*(4-mo)	*R*(6-mo)
10	–3, +5	–4	+2	+3
11	–2	–2	–2	0
12	–4, +3	+2	+1	+1
13	–4	–4	0	0
14	–9, –1, +1, +3	–5	+5	–3
15	–3, –2	–3	–3	–2
16	0, +5	+5	+5	–3
17	–1	+2	+2	+1
18	+2	+3	+3	+2
19	–3, +2	–3	–4	–1
20	–3	0	–2	–2
21	+1	–5	–5	–6
22	–3	+5	+4	–2

While the minimum values of *R* do not correlate well against the values of *Rm*, the minimum values of the 2-, 4-, and 6-month moving averages do. This is shown in figure 1 which displays scatter plots of *Rm* versus the minimum values of the 2-month moving average (left), the 4-month moving average (middle), and the 6-month moving average (right). Identified for each is the regression equation ($\hat{y}$, depicted as the thick diagonal line), the coefficient of correlation (r), the coefficient of determination (r^2, a measure of the amount of variance that the regression can explain), and the standard error of estimate (*se*), as well as the 2 by 2 contingency tables (formed by the median values of the parameters and displayed as the thin vertical and horizontal lines) which, by means of Fisher's exact test,[12] allows one to compute the probability *P* that the observed result, or one more suggestive of a departure from independence, is due entirely to chance.

Above each scatter plot is a plot of the ratio of the observed *Rm* to the predicted *Rm* (deduced from the regression equation $\hat{y}$). One finds that, based on the minimum value of the 2-month moving average, the observed value for *Rm* typically lies within 30 percent of the predicted value (true for 10 of 13 cycles). Similarly, from the minimum values of the 4- or 6-month moving averages, one finds that the observed value for *Rm* typically lies within 20 percent of the predicted value (true for 11 of 13 cycles).

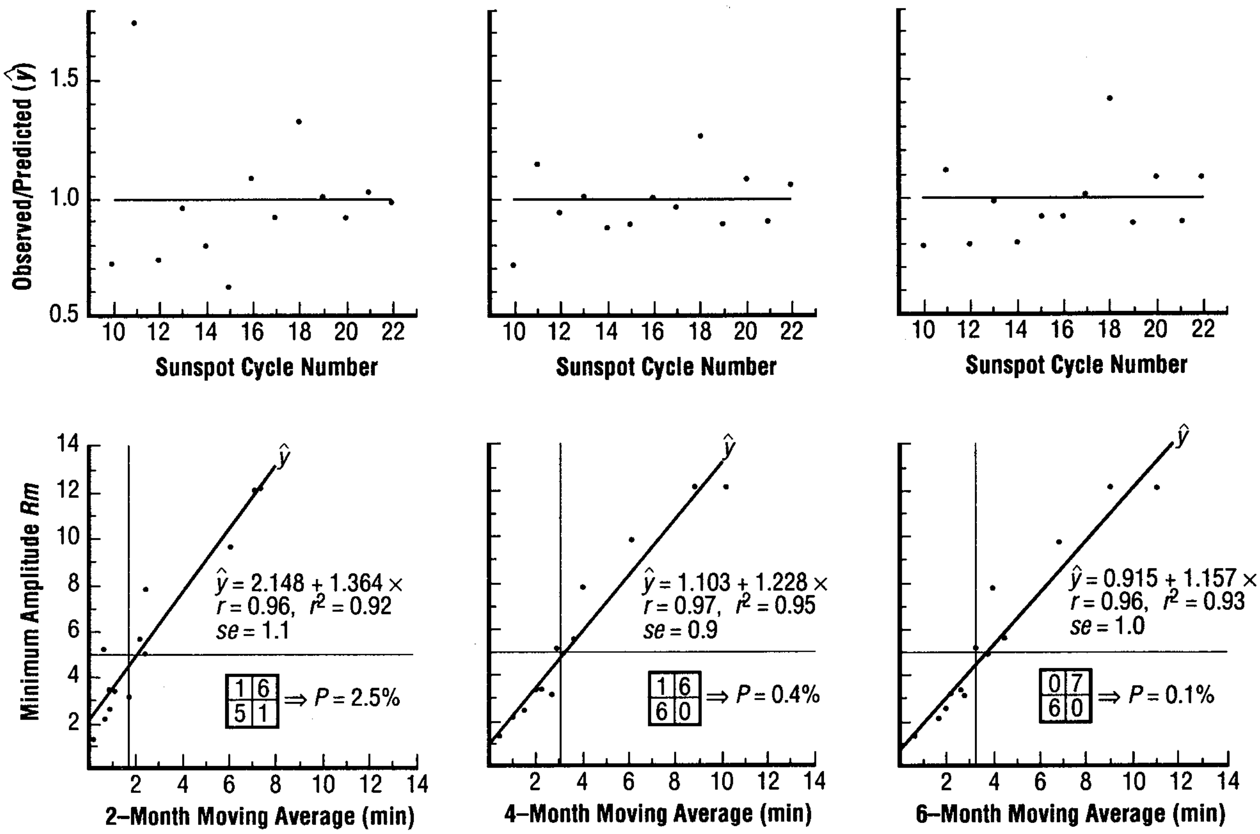

FIGURE 1.— Scatter plots of minimum amplitude *Rm* versus the 2-month moving average (left), the 4-month moving average (middle), and the 6-month moving average (right).

IV. DISCUSSION

Table 4 gives the monthly mean values of sunspot number *R*, as well as the 2-, 4-, 6-, and 12-month moving averages, for the timespan of June 1995 through October 1996. At present (November 1996), the 12-month moving average, *R*(12-mo), is known only through April 1996, the lowest observed value being the April 1996 value of 8.6, slightly lower than the 9.8 value found for March 1996. While the minimum value in the 12-month moving average has not yet been seen and is probably still several months away (i.e., probably occurring sometime during the interval of September 1996 to March 1997 that has been previously identified as the interval most likely to contain the date of minimum amplitude occurrence for cycle 23; certainly, it must occur before September 1997, if, indeed, cycle 22 is a short-period cycle[4,5]), it should be noted that the current values of the 12-month moving average are now within the range of previously observed minimum amplitude values (i.e., 1.5–12.3, with 10 of 13 modern era cycles having $Rm \le 7.7$; only cycles 20, 21, and 22 have had *Rm* of higher value, being 9.6, 12.2, and 12.3, respectively).

TABLE 4.—*The decline of cycle 22.*

Year-Month	R	2-Month	4-Month	6-Month	12-Month
1995					
J	15.6	15.1	14.7	15.7	18.2
J	14.5	14.7	14.4	14.7	17.0
A	14.3	13.7	14.7	14.8	15.4
S	11.8	14.8	14.7	13.9	13.4
O	21.1	15.8	13.5	13.2	12.2
N	9.0	12.3	12.9	12.1	11.4
D	10.0	10.1	10.8	11.1	10.8
1996					
J	11.5	9.4	8.8	9.5	10.5
F	4.4	7.4	8.2	7.9	10.2
M	9.2	7.0	6.8	7.8	9.8
A	5.1	6.3	7.0	7.7	8.6
M	5.6	7.0	7.9	8.3	
J	11.8	9.5	8.9	8.5	
J	8.8	10.9	9.6	7.6	
A	14.0	9.7	7.9		
S	1.8	4.9			Interval when cycle 23 sunspot minimum is expected, if cycle 22 is a short-period cycle
O	1.8				
N					
D					
1997					
J					
F					
M					

On the basis of monthly mean sunspot number *R*, a local minimum of 4.4 was seen in February 1996, near to local minimum occurrence dates that have been seen for the shorter length moving averages (see below). While this value is low, clearly, it should have been recognized that it very probably was not the minimum value for *R* for cycle 23, because the value of 4.4 is a value that lies well outside the range of previously observed minimum values for *R*(0.0–3.1), and is, in fact, more than four standard deviation units above the mean of 0.6 for the modern era cycles, with only 3 of 13 cycles having a minimum value >0.5 (including cycles 20, 21, and 22 which had minimum values measuring, respectively, 3.1, 1.9, and 1.1).

More recently, *R* has dipped below 4.4 to a value of 1.8 in both September and October 1996. Perhaps, now we are very close to what will actually become the date for the minimum value of *R* for cycle 23. The value of 1.8 is within the range of previously observed minimum values for *R*(0–3.1), although it is higher than the minimum value for *R* for the bulk of the modern era cycles (≤ 0.5). Accepting 1.8 as the minimum value of *R* for cycle 23 suggests that minimum amplitude *Rm* for cycle 23 probably has not yet occurred (i.e., about March 1996 as was recently proclaimed; e.g., see *Solar News* for August and September 1996), although its occurrence seems most imminent (i.e., any time between June 1996 and March 1997).

For the 2-month moving average, *R*(2-mo), a local minimum of 6.3 was seen in April 1996, although a lower value of 4.9 was seen more recently in September 1996. The value of 4.9, while within the range of minimum values that has been seen for the 2-month moving average (0.2–7.5), is still higher than the minimum value for the majority of modern era cycles (≤ 2.6). Thus, the 2-month moving average for October 1996 may possibly be even lower than the September value of 4.9, this being true only if the November 1996 value of *R* is < 14.0. For the 2-month moving average to fall below 2.6, the November 1996 value of *R* must be <5.0. Accepting 4.9 as the minimum value for the 2-month moving average (probably a rather dubious choice) suggests that minimum amplitude occurrence should not be expected until sometime between April 1996 and February 1997.

For the 4-month moving average, *R*(4-mo), its lowest observed value has been the one for March 1996, measuring 6.8 in value, a value that, while being within the range of previously observed values (0.5–10.2), is higher than most (≤ 4.0). Following the local minimum of 6.8 in March 1996, the 4-month moving average rose to 9.6 in July 1996, but is now decreasing in value (7.9 in August 1996). The 4-month moving average for September 1996 will be <6.8 if the November 1996 value for *R* is <10.4. The September 1996 value for the 4-month moving average, however, will not be < 4.0, because for this to happen, the November 1996 value of *R* would have to be negative in value (–6.0 or lower), physically impossible. Thus, for the 4-month moving average to drop below 4.0, the monthly mean sunspot numbers for late 1996 and possibly early 1997 should be relatively low in value.

For the 6-month moving average, *R*(6-mo), the lowest observed value that has been seen thus far is the value of 7.6 which was seen in July 1996, slightly below the values of 7.8 and 7.7 observed in March and April 1996, respectively. While the value of 7.6 is within the range of previously observed minimum values for the 6-month moving average (0.6–11.1), like the 2- and 4-month moving averages and the monthly value of *R*, it is a value that is higher than that which has been seen for the bulk of the modern era sunspot cycles (≤ 4.4). Therefore, we expect the 6-month moving average to further decrease in value during the latter portion of 1996.

If indeed minimum amplitude is to occur sometime during the interval of September 1996 to March 1997 as has been predicted,[4–7] then values lower than those presented above for R(2-mo), R(4-mo), R(6-mo), R(12-mo), and possibly even R will likely be reported. Still, one can begin to use the lowest observed values of the moving averages *as if they are the actual minimum values* of the moving averages in order to gauge both the expected size of minimum amplitude Rm for cycle 23 (by means of the regression equations that are shown in fig. 1) and its placement. For example, the lowest observed value of 4.9 for the 2-month moving average, should it turn out to be the minimum value, suggests an $Rm = 8.8 \pm 2.0$ (at the 90-percent level of confidence) that should occur on or after April 1996 (and before March 1997). Similarly, the lowest observed value of 6.8 for the 4-month moving average, should it turn out to be the minimum value (very doubtful), suggests an $Rm = 9.5 \pm 1.6$ that should occur on or after October 1995 and before August 1996, while the lowest observed value of 7.6 for the 6-month moving average, should it turn out to be the minimum, suggests an $Rm = 9.7 \pm 1.8$ that should occur on or after April 1996 and before October 1996. Taken together, these values, presuming that they are indeed the minimum values of the shorter length moving averages, suggest a value of about 7.9 to 10.8 for cycle 23's Rm that should occur sometime between April and August 1996 (based on the overlap).

Any date for minimum amplitude occurrence for cycle 23 before August 1996, deduced from the tentative occurrence dates for the minimum values of the shorter length moving averages, however, seems too early to truly be considered genuine, especially, in light of the current behavior of R and the first occurrence of a new cycle, high-latitude spot for cycle 23 in May 1996 which suggests minimum amplitude for cycle 23 on or after about July 1996. Likewise, any date for minimum amplitude for cycle 23 prior to September 1996 suggests a period for cycle 22 that clearly is outside the lower limit of observed cycle lengths for the modern era cycles (120 months), with any period ≤ 117 months (inferring Rm for cycle 23 on or before June 1996) considered highly unlikely, having a probability of occurrence of only 2.5 percent, based on the statistics of the modern era short-period cycles. Consequently, it seems much more reasonable to believe that values lower than those already experienced for the 2-, 4-, 6-, and 12-month moving averages (and possibly even R) probably will occur later in 1996.

Supporting this notion is the continued delay in witnessing the transition of the cycle from one that is dominated by old cycle, low-latitude spots to one that is dominated by new cycle, high-latitude spots, a behavior that has been characteristic of sunspot cycles near their minimums.[4] Figure 2 displays the latitude distribution of sunspots between January 1995 and October 1996. While it is apparent that the first occurrence of a new cycle, high-latitude (i.e., $\geq 25°$) spot occurred in May 1996 and that with each succeeding month new cycle, high-latitude spots have continued to be reported, they have been relatively small in area and short-lived; consequently, they have not contributed greatly to the value of the weighted mean latitude, identified as the line running through the dotted latitudinal field. Past experience has shown that there is a strong transition to values $>20°$ in the vicinity of minimum amplitude occurrence.[4] Inspection of figure 2 suggests that the weighted mean latitude has yet to show this strong shift, although a slow shift to higher value seems to be underway (beginning about March 1996). Values of the weighted mean latitude remain below 20°, indicating the continued dominance of old cycle, low-latitude spots.

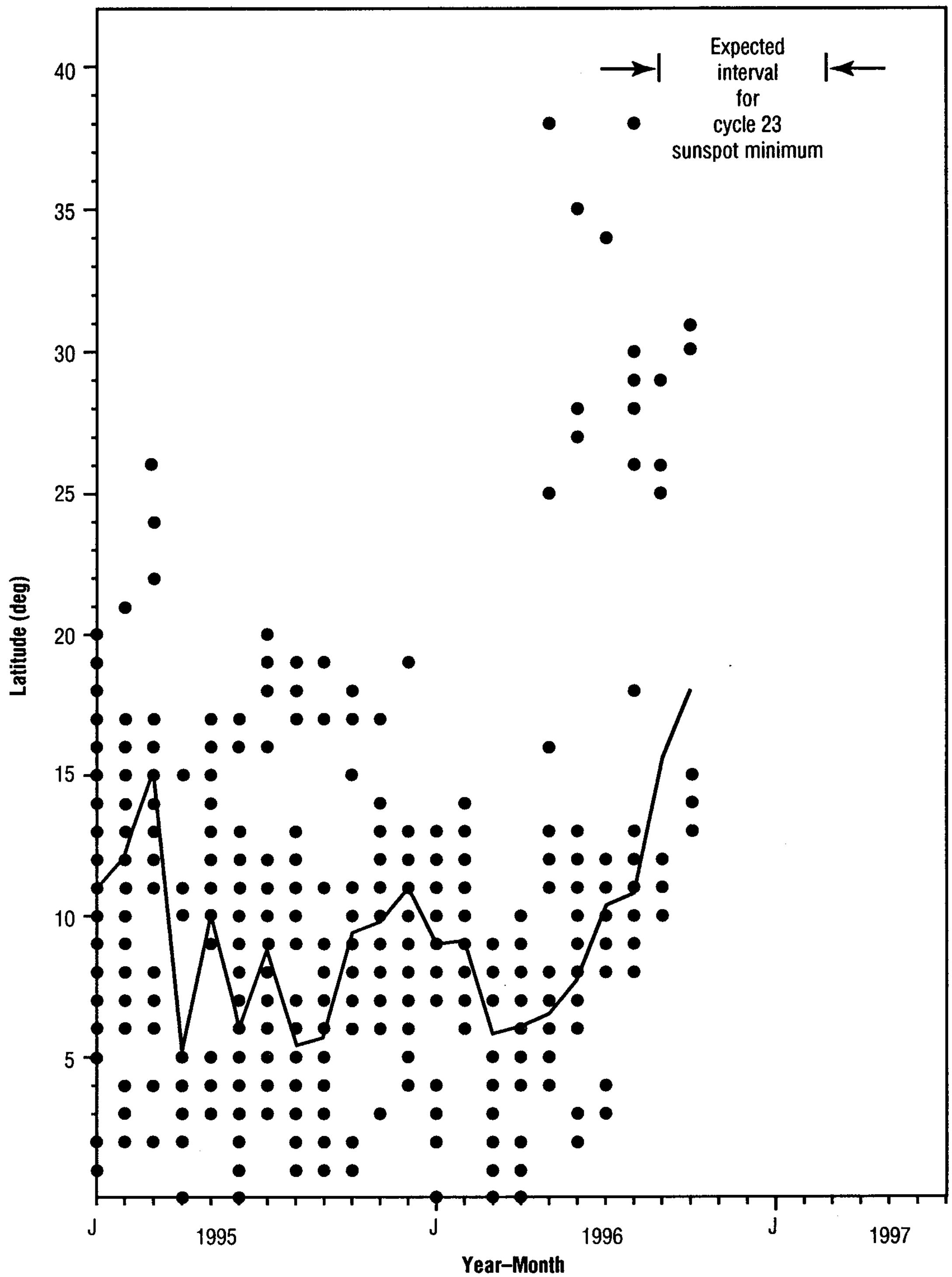

FIGURE 2.—Latitudinal distribution of sunspots for January 1995 through October 1996. Individual dots represent the latitudinal position of sunspots (disregarding hemispheric location).

Also supporting the notion that sunspot minimum for cycle 23 has yet to occur is the behavior of the Mg II index, a solar ultraviolet variability index derived from the daily solar spectrum measured by the Solar Ultraviolet Spectral Irradiance Monitor on the Upper Atmospheric Research Satellite, depicted as monthly means in figure 3. Clearly, both monthly means (the jagged, thin line) and 12-month moving average values (the smooth, heavier line) of the Mg II index have continued to track downward through October and April 1996, respectively.

In conclusion, this study has shown that the values of the monthly mean sunspot number and of moving averages of shorter length can be used to not only gauge the size of the minimum amplitude *Rm* but also to gauge the nearness of minimum amplitude occurrence. Although a minimum in the 12-month moving average has not, as yet, been seen (smoothed sunspot number measured 8.6 in April 1996, the last available entry for *R*(12-mo) and the trend remained downward), local minima in shorter length moving averages were seen in early 1996 (although we expect that these local minima will be eclipsed in the latter portion of 1996). Accepting these minimum values as the actual minimums for the parameters (that are associated with the onset of a sunspot cycle) suggests that *Rm* for cycle 23 will be considerably higher than average, being about 7.9 to 10.8, and that *Rm* for cycle 23 should be expected anytime after about March 1996, and possibly before September 1996. On the other hand, because the latitudinal distribution of spots at the current time (through October 1996) remains one that is dominated by old cycle, low-latitude spots and because minimum amplitude for a sunspot cycle has always followed the first occurrence of a new cycle, high-latitude spot (without exception) by at least 3 months, it is inferred that minimum amplitude for cycle 23 probably has not yet occurred (i.e., in early 1996) and that it should not occur until after about July 1996, probably during the interval of September 1996 to March 1997 (based on the range of observed periods for the short-period modern era sunspot cycles). The recent low of 1.8 for monthly mean sunspot number in September and October 1996 also seems to support an expected later-occurring minimum amplitude for cycle 23 (on or later than June 1996), as does the behavior of the Mg II index. Thus, the local minima that have been observed for the shorter length moving averages probably will be eclipsed in the latter portion of 1996, inferring that *R*(12-mo) will fall below 8.6, indicating that *Rm* for cycle 23 will be <8.6.

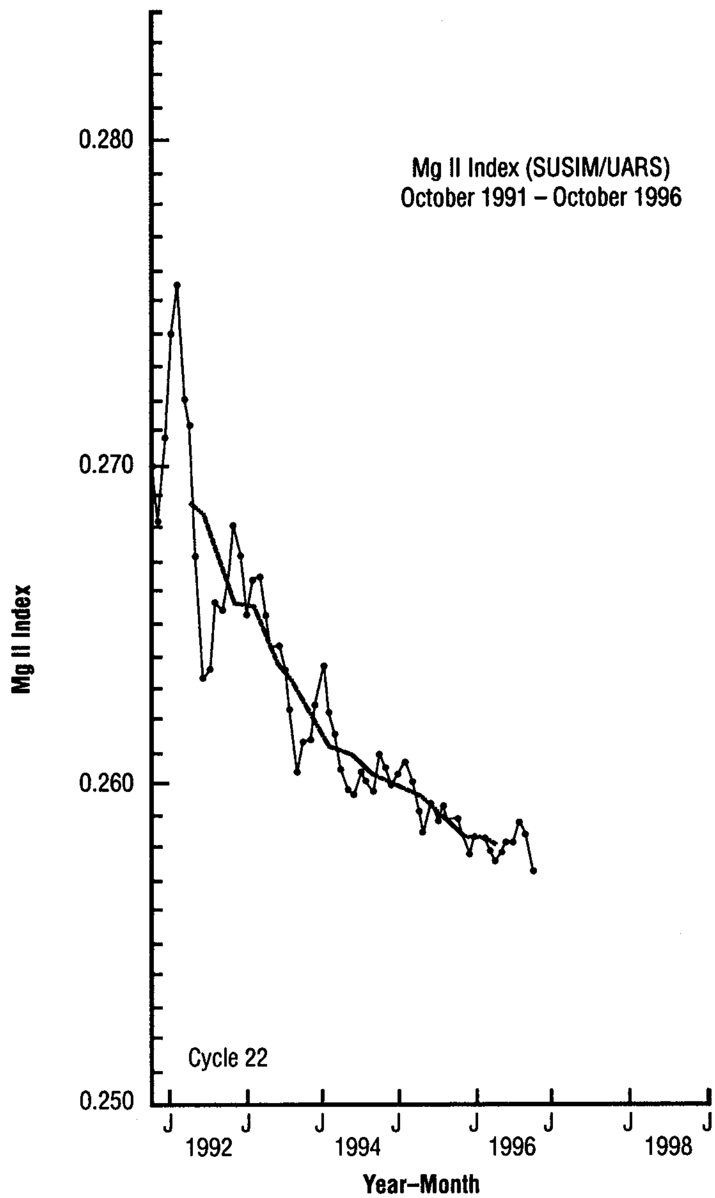

FIGURE 3.—The Mg II index for October 1991 to October 1996. Monthly means are plotted as the thin line and the smoothed (or 12-month moving average) data as the heavy line.

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13. ABSTRACT *(Maximum 200 words)*

By definition, the conventional onset for the start of a sunspot cycle is the time when smoothed sunspot number (i.e., the 12-month moving average) has decreased to its minimum value (called minimum amplitude) prior to the rise to its maximum value (called maximum amplitude) for the given sunspot cycle. On the basis of the modern era sunspot cycles 10–22 and on the presumption that cycle 22 is a short-period cycle having a cycle length of 120 to 126 months (the observed range of short-period modern era cycles), conventional onset for cycle 23 should not occur until sometime between September 1996 and March 1997, certainly between June 1996 and June 1997, based on the 95-percent confidence level deduced from the mean and standard deviation of period for the sample of six short-period modern era cycles.

Also, because the first occurrence of a new cycle, high-latitude (≥ 25 degrees) spot has always preceded conventional onset of the new cycle by at least 3 months (for the data-available interval of cycles 12–22), conventional onset for cycle 23 is not expected until about August 1996 or later, based on the first occurrence of a new cycle 23, high-latitude spot during the decline of old cycle 22 in May 1996. Although much excitement for an earlier-occurring minimum (about March 1996) for cycle 23 was voiced earlier this year, the present study shows that this exuberance is unfounded. The decline of cycle 22 continues to favor cycle 23 minimum sometime during the latter portion of 1996 to the early portion of 1997.

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