PREDICTING THE SIZE AND TIMING OF THE NEXT SOLAR CYCLE: PAPER I, BASED ON SUNSPOT NUMBER

Robert M. Wilson
NASA Marshall Space Flight Center, NSSTC, Huntsville, Alabama

robert.m.wilson@nasa.gov

ABSTRACT

This paper (Paper 1) provides estimates of the period (PER) for sunspot cycle (SC)24, the current ongoing solar cycle, and the timing and size of the next solar cycle, SC25. Presently, smoothed sunspot number *R* for SC24 continues to decrease with time, essentially being flat through 2018 into 2019 (measuring 6.0 in December 2018). The analyses presented herein strongly suggest that SC24, a slow-rising SC of small maximum amplitude, is also a cycle of long period (PER $\geq$ 135 months), inferring that the epoch of sunspot minimum (Em) for SC25 likely will occur on or later than March 2020. If true, then the epoch of sunspot maximum (EM) for SC25 likely will occur on or later than April 2024 and probably be of small maximum amplitude (RM < 184), but of greater maximum amplitude than was seen in SC24 (RM = 116.4), presuming that SC25 will not be a statistical outlier with respect to the even-odd cycle effect. The minimum interval for SC24/25 appears similar to that experienced during the preceding minimum interval of SC23/24, but possibly slightly longer.

INTRODUCTION

Predicting the overall behavior (i.e., timing, size and duration) of a future SC is crucially important for forecasting solar cycle effects in the near-Earth and interplanetary space environment, solar irradiance, space weather, radio communications, power distribution systems, etc. (Withbroe 1989; Song, Singer, and Siscoe 2001; Clilverd et al. 2003; Hathaway, 2015). To accomplish this task, various techniques have been developed, including precursor methods, extrapolation methods, model-based methods, spectral methods, and neural networks (e.g., Hathaway, Wilson and Reichmann 1999; Hathaway 2008; Petrovay 2010; Pesnell 2012). In this paper, the expected duration of SC24, the present ongoing SC, and the size and timing of SC25 are investigated using specific SC parameters gleaned from the behavior of ongoing SC24. In a companion paper (Paper 2), the expected size and timing of SC25 will be examined using the strength of the *Aa* and *Ap* geomagnetic index values.

METHODS AND MATERIALS

To perform this study, smoothed monthly mean sunspot number (*R*) has been taken from the Solar Influences Data Analysis Center (SIDC), available online at www.sidc.be/silso, using version 2.0, the newly revised sunspot number dataset (Clette et al. 2015; Wilson 2015). Smoothed monthly mean sunspot number is the 12-month moving average of monthly mean sunspot number (also called the 13-month running mean of monthly mean sunspot number). This investigation uses both linear regression analysis and nonparametric analyses (i.e., Fisher's exact test for 2×2 contingency tables and Kendall's τ) (Everitt 1977; Gibbons 1993).

RESULTS AND DISCUSSION

The dotted line in figure 1 displays *R*-values for the interval December 2005 through December 2018 (the last available *R* at the time of writing this paper), thereby covering the last three years of SC23 and the onset, ascent, maximum, and descent of SC24. As of December 2018, SC24 has persisted some 120 months based on *R*. Minimum smoothed monthly mean sunspot number (Rm) occurred in December 2008 (the epoch of cycle minimum, Em, identified by the unfilled triangle) and measured 2.2. SC24 attained its first maximum in March 2012, measuring 98.3, and its overall cyclic maximum (RM) in April 2014 (the epoch of cycle maximum, EM, identified by the filled triangle), measuring 116.4. Thus, SC24 had an ascent duration (ASC) of 64 months, the fifth longest on record (ASC has spanned 35–82 months, having a mean of 52.3 months and a standard deviation, *sd*, measuring 13.6 months). Since EM, SC24's *R*-values have decreased to $R = 6.0$ in December 2018, a value well within the range of previously observed Rm values for SC1–SC24, which spans 0.0–18.6, having a mean of 9.3 and $sd = 5.7$. Hence, Em for SC25, the next SC, is believed to be very near, probably occurring sometime between late 2019 and the end of 2021 (cf. Uzal, Piacentini, and Verdes 2012). Because of the large number of spotless days (Wilson 2017) now being seen, *R*-values are expected to continue to decrease falling below $R = 6.0$. Relative to previous cycles, SC24's RM is the fourth smallest SC on record (cf. Svalgaard, Cliver, and Kamide 2005). Likewise, the expected Rm value for SC25 will be among the lowest observed (0.0–5.9).

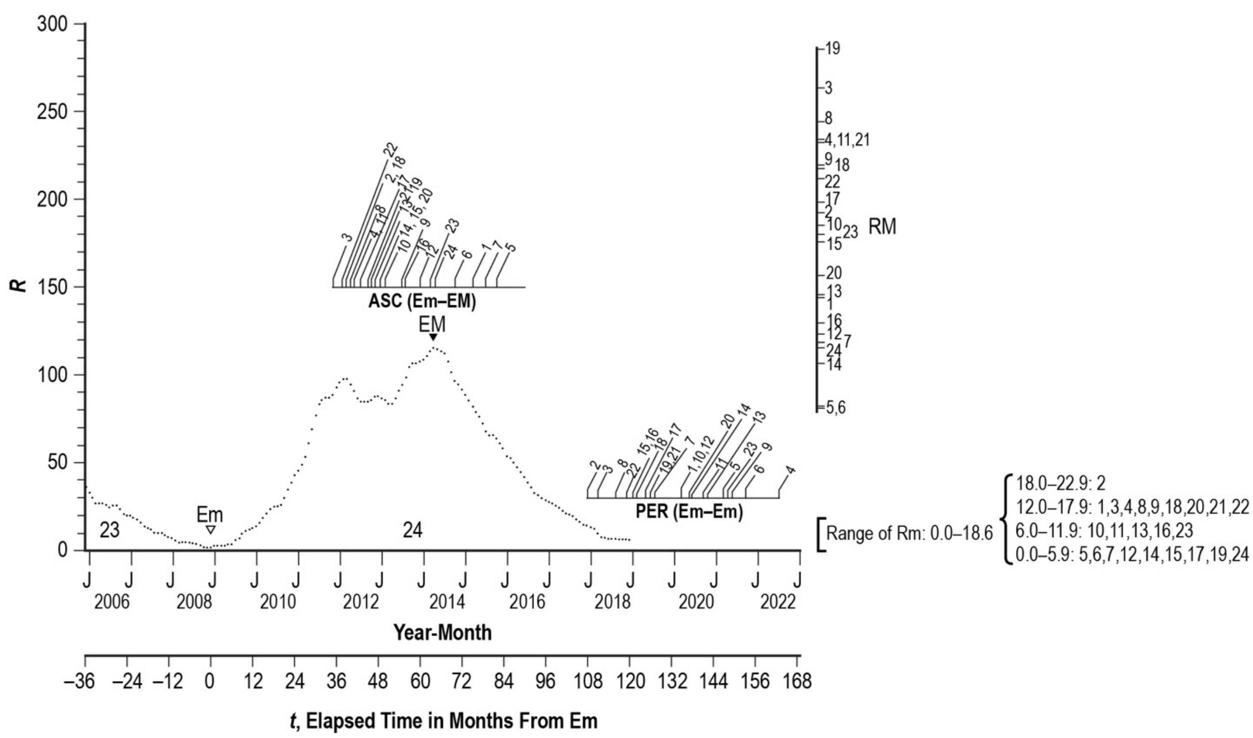

Figure 1. Variation of smoothed sunspot number (*R*) December 2005–December 2018. The epochs of sunspot minimum (Em) and maximum (EM) are identified for sunspot cycle (SC)24. Also shown are the relative occurrences of the ascent (ASC) durations, maximum amplitudes (RM) and periods (PER) for SC1–SC24, as well as the range of minimum amplitudes for specific groupings. The individual numbers 1–24 refer to the individual SCs. *t* is the elapsed time in months from Em.

Figure 2 shows the month-to-month change in R-values. SC24's greatest positive change in R ($gp\Delta R$) occurred in April 2011, measuring 8.2, some 3 years prior to EM. Its greatest negative change in R ($gn\Delta R$) occurred in August 2014, measuring –6.4, a mere 4 months following EM. Relative to previous cycles, SC24's $gp\Delta R$ value is the ninth smallest, and its $gn\Delta R$ value is the fifth smallest. In Figure 2, t_1 is the elapsed time in months from Em to $gp\Delta R$ occurrence, t_2 is the elapsed time in months from $gp\Delta R$ occurrence to EM, t_3 is the elapsed time in months from EM to $gn\Delta R$ occurrence, and t_4 is the elapsed time in months from $gn\Delta R$ occurrence to Em for SC (n+1). The ΔR-value signature (i.e., positive-negative-positive peaks) merely reflects the double-peaked nature of SC24. (For convenience, Tables 1 and 2 are included to give the reader specific information regarding parameters that will be discussed in the following charts.)

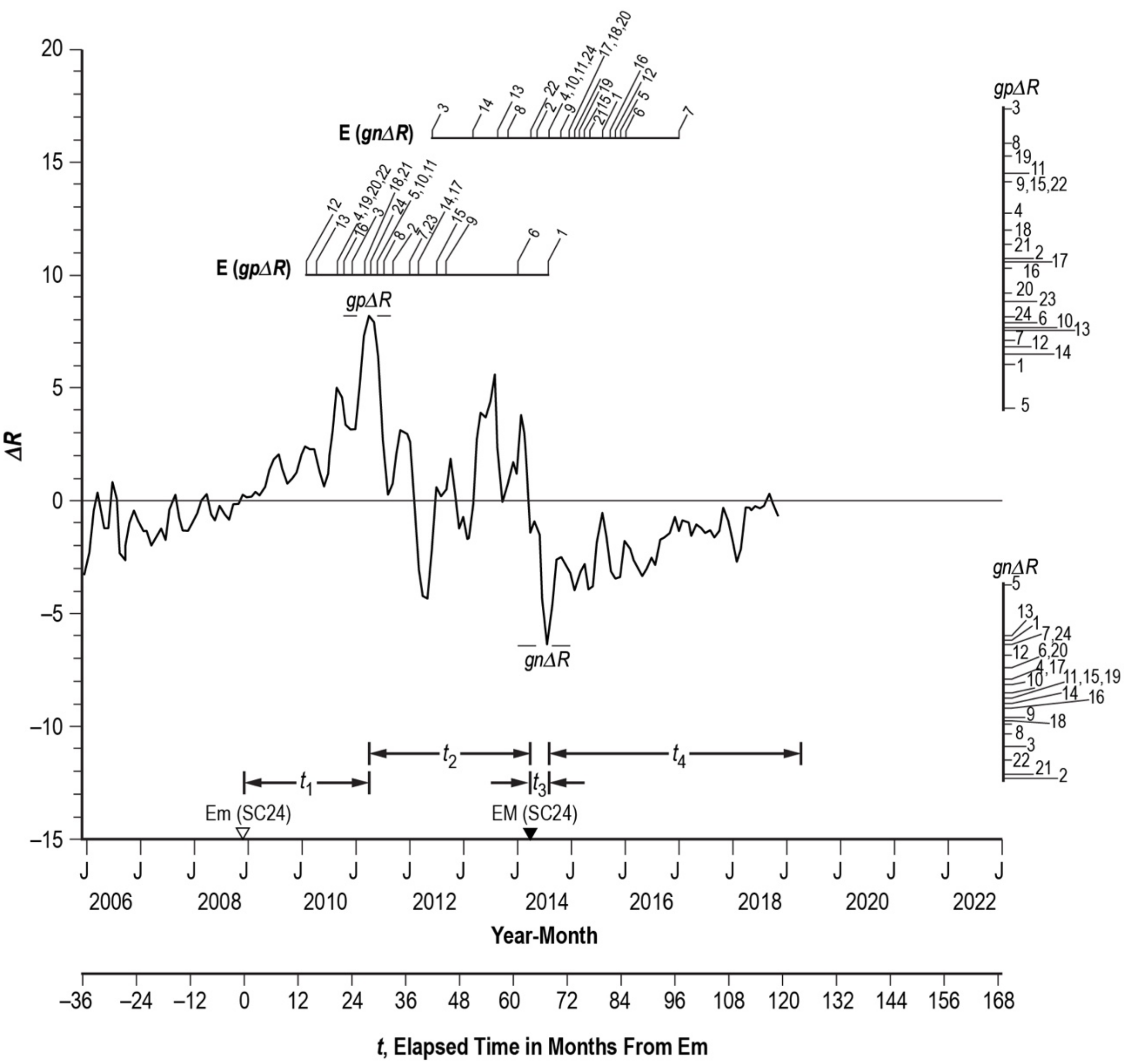

Figure 2. Variation of the rate of change in R (ΔR) for the interval December 2005–November 2018. Also shown are the relative occurrences and amplitudes of the greatest positive ($gp\Delta R$) and greatest negative ($gn\Delta R$) rates of change in R for SC1–SC24. t is the elapsed time in months from Em.

Table 1. Parametric values for SC1–SC24.

SC	Em	EM	Rm	RM	ASC	DES	PER	SLOPE (ASC)	SLOPE (DES)	$gp\Delta R$	$gn\Delta R$	t_1	t_2	t_3	t_4	Class
01	1755-03	1761-06	14.0	144.1	75	60	135	1.7347	–2.0917	6.0	–6.2	68	7	5	55	SL
02	1766-06	1769-09	18.6	193.0	39	69	108	4.4718	–2.6232	10.7	–12.3	33	6	26	43	FS
03	1775-06	1778-05	12.0	264.3	35	76	111	7.2086	–3.2684	17.4	–10.9	24	11	7	69	FS
04	1784-09	1788-02	15.9	235.3	41	122	163	5.3512	–1.8852	12.7	–7.9	21	20	27	95	FL
05	1798-04	1805-02	5.3	82.0	82	65	147	0.9354	–1.2615	4.1	–3.7	30	52	2	63	SL
06	1810-07	1816-05	0.0	81.2	70	83	153	1.1600	–0.9759	5.9	–7.4	61	9	15	68	SL
07	1823-04	1829-11	0.2	119.2	79	48	127	1.5063	–2.2292	5.1	–6.3	37	42	18	30	SS
08	1833-11	1837-03	12.2	244.9	40	76	116	5.8175	–2.9908	15.8	–10.3	31	9	19	57	FS
09	1843-07	1848-02	17.6	219.9	55	94	149	3.6782	–2.2755	14.1	–9.6	45	10	16	78	SL
10	1855-12	1860-02	6.0	186.2	50	85	135	3.6040	–2.0741	7.7	–8.1	30	19	19	66	SL
11	1867-03	1870-08	9.9	234.0	41	100	141	5.4659	–2.3030	15.5	–8.7	30	11	27	73	FL
12	1878-12	1883-12	3.7	124.4	60	75	135	2.0117	–1.5480	6.8	–6.8	14	46	23	52	SL
13	1890-03	1894-01	8.3	146.5	46	96	142	3.0043	–1.4792	7.6	–6.0	16	30	11	85	FL
14	1902-01	1906-02	4.5	107.1	49	89	138	2.0939	–1.1753	6.5#	–9.0	39	10	2	87	SL
15	1913-07	1917-08	2.5	175.7	49	72	121	3.5347	–2.3097	14.2	–8.8	43	6	27	45	SS
16	1923-08	1928-04	9.4	130.2	56	65	121	2.1571	–1.9138	10.3	–9.2	22	34	26	39	SS
17	1933-09	1937-04	5.8	198.6	43	82	125	4.4837	–2.2646	10.6	–7.9	39	4	30	52	FS
18	1944-02	1947-05	12.9	218.7	39	83	122	5.2769	–2.5735	12.0	–9.7	27	12	34	49	FS
19	1954-04	1958-03	5.1	285.0	47	79	126	5.9553	–3.4266	15.3	–8.8	22	25	28	51	FS
20	1964-10	1968-11	14.3	156.6	49	88	137	2.9041	–1.5773	9.2	–7.5	22	27	24	64	SL
21	1976-03	1979-12	17.8	232.9	45	81	126	4.7800	–2.7086	11.4	–12.1	27	18	32	49	FS
22	1986-09	1989-11	13.5	212.5	38	81	119	5.2368	–2.4852	14.2	–11.5	21	17	26	55	FS
23	1996-08	2001-11	11.2	180.3	63	85	148	2.6841	–2.0953	8.8	–7.9	37	26	11	74	SL
24	2008-12	2014-04	2.2	116.4	64	–	–	1.7844	–	8.2	–6.4	28	36	4	–	S?
		mean	9.3	178.7	52.3	80.6	132.4	3.6184	–2.1537	10.4	–8.5	32.0	20.3	19.1	60.8	
		sd	5.7	57.8	13.6	15.0	14.1	1.7598	0.6359	3.8	2.1	12.9	13.7	9.9	16.3	

Note: SC24 DES >56, PER >120 (R values known thru December 2018)
SC means Sunspot Cycle
Em means Epoch of sunspot minimum (i.e., the occurrence of Rm)
EM means Epoch of sunspot maximum (i.e., the occurrence of RM)
Rm is the minimum value of the smoothed monthly mean sunspot number (i.e., the 12-month moving average of R)
RM is the maximum value of the smoothed monthly mean sunspot number (i.e., the 12-month moving average of R)
ASC is the elapsed time in months from Em to EM
DES is the elapsed time in months from RM (n) to Rm (n + 1)
PER is the Period or elapsed time in months from Em (n) to Em (n + 1) or ASC + DES or $t_1 + t_2 + t_3 + t_4$
SLOPE (ASC) = (RM – Rm)/ASC
SLOPE (DES) = (Rm (n + 1) – RM)/DES
$gp\Delta R$ is the greatest positive value in the difference of consecutive monthly smoothed R values during ASC

$gn\Delta R$ is the greatest negative value in the difference of consecutive monthly smoothed R values during DES

means a larger value (7.5) was observed after RM during SC14 decline

t_1 means time in months between Em and E ($gp\Delta R$)

t_2 means time in months between E ($gp\Delta R$) and RM

t_3 means time in months between RM and E ($gn\Delta R$)

t_4 means time in months between E ($gn\Delta R$) and Em (n + 1)

$t_1 + t_2$ = ASC

$t_3 + t_4$ = DES

$t_1 + t_2 + t_3 + t_4$ = ASC + DES = PER

FS means Fast ASC (ASC <49 months), Short PER (PER <135 months)

FL means Fast ASC, Long PER (Per ≥ 135 months)

SS means Slow ASC (ASC ≥ 49 months), Short PER

SL means Slow ASC, Long PER

Table 2. Parametric means (standard deviations) for selected groupings of sunspot cycles.

Class		RM	ASC	DES#	PER#
Fast Rise (11)	12.0(4.5)	224.2(37.2)	41.3(3.7)	78.0(27.1)	127.2(16.0)
Slow Rise (13)	7.0(5.8)	147.3(43.4)	61.6(11.8)	75.8(14.0)	137.2(10.6)
Short Period (11)	10.0(6.0)	206.8(51.5)	46.4(12.4)	73.8(10.3)	120.2(6.3)
Long Period (12)	9.2(5.5)	158.1(54.4)	58.4(15.4)	86.8(16.3)	143.6(8.7)
Even (12)	9.4(6.0)	167.2(55.0)	49.6(10.9)	83.3(14.9)	131.5(16.4)
Odd (12)	9.1(5.6)	190.2(60.5)	55.0(15.9)	78.2(15.3)	133.2(12.3)
FS (8)	12.2(4.9)	231.2(32.1)	40.8(4.0)	78.4(4.6)	119.1(6.9)
FL (3)	11.4(4.0)	205.3(50.9)	42.7(2.9)	106.0(14.0)	148.7(12.4)
SS (3)	4.0(4.8)	141.7(30.0)	61.3(15.7)	61.7(12.3)	123.0(3.5)
SL (9)	8.5(5.9)	142.4(48.1)	61.4(12.1)	80.4(11.4)	141.9(7.2)

Note: # means DES and PER for SC24 remain unknown at present

Figure 3 displays the cyclic values of Rm, RM, ASC, DES (i.e., the descent duration), PER (i.e., the period or ASC + DES), SLOPE(ASC), SLOPE(DES), $gp\Delta R$ and $gn\Delta R$ for SC1–24. Similarly, Figure 4 depicts the cyclic values of t_1, t_2, t_3, and t_4 for SC1–SC24. Now, SLOPE(ASC) is simply computed as (RM – Rm)/ASC for cycle n and SLOPE(DES) is computed as (Rm (cycle n + 1) – RM (cycle n)) / DES (cycle n). Close inspection of ASC and DES for an SC reveals that, generally speaking, DES > ASC for an SC in 20 of 23 cycles. The only exceptions are the early-occurring, less-reliably determined cycles 1, 5, and 7. Hence, one expects SC24's DES >64 months, inferring that Em for SC25 should occur sometime after elapsed time t = 128 months (i.e., after August 2019). Since SC7, the smallest difference between ASC and DES is 9 months, suggesting that SC24's DES ≥73 months, inferring that Em for SC25 probably should not be expected until on or after May 2020. Based on the mean value of DES (80.6 ± 15 months), one does not expect SC25 Em to occur until about t = 145 ± 15 months (i.e., on or after about October 2019). Also, because there is a noticeable gap in PER between 127 and 135 months, one really does not expect SC24's PER to fall within the gap, inferring that Em for SC25 should not be expected until on or after PER = 135 months (i.e., on or after March 2020), especially considering the previous findings. Based on the mean value of t_4 (= 60.8 months), one does not expect Em for SC25 until on or after August 2019.

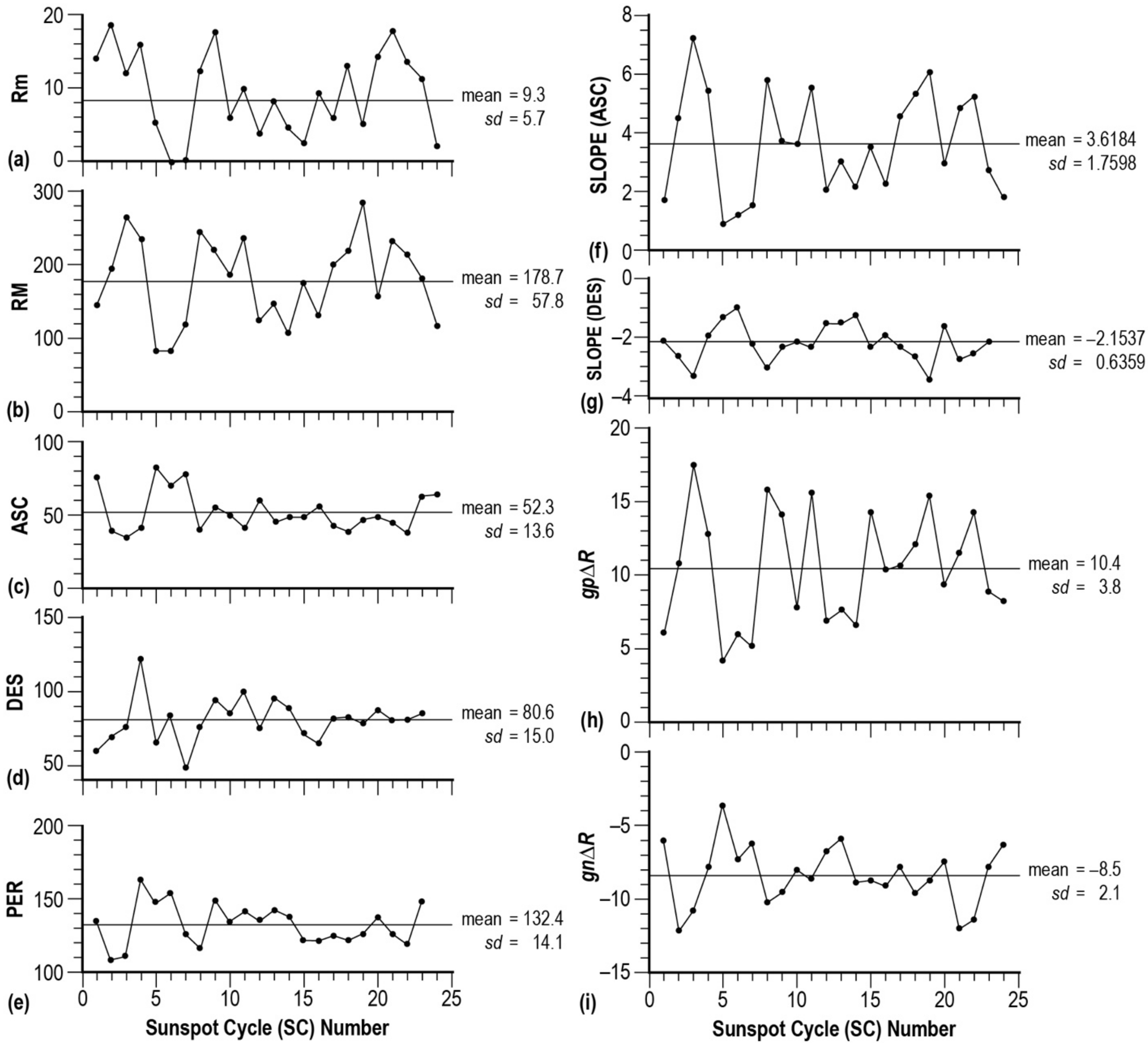

Figure 3. Variation of cyclic values of (a) Rm, (b) RM, (c) ASC, (d) DES (i.e., the descent duration), (e) PER (i.e., the period or ASC + DES), (f) SLOPE (ASC), (g) SLOPE (DES), (h) *gpΔR* and (i) *gnΔR* for SC1–SC24. Also given are the parametric means and standard deviations (*sd*).

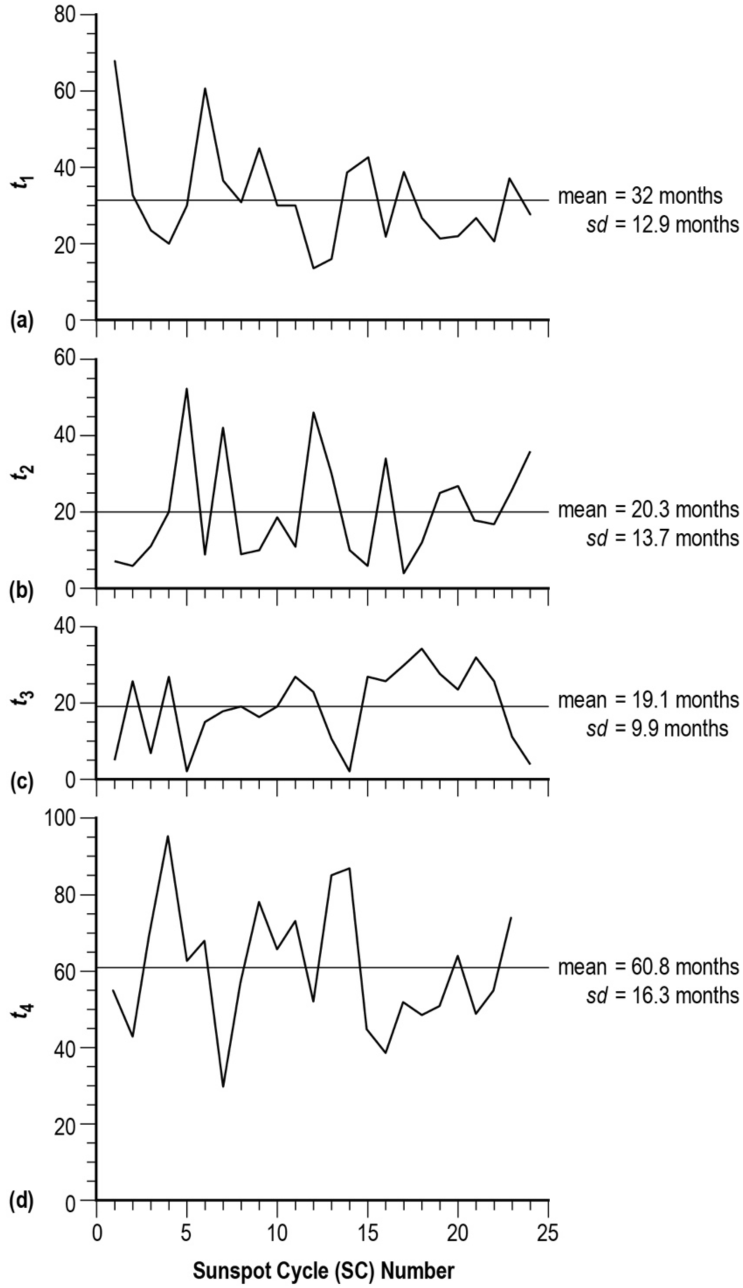

Figure 4. Variation of (a) t_1, (b) t_2, (c) t_3, and (d) t_4 for SC1–SC24, where these parameters are defined in the note given in Table 1.

Figure 5 depicts scatterplots of RM versus (a) *gpΔR* and (b) ASC for cycle *n*. Shown in both scatterplots are the results of linear regression analysis and nonparametric analyses. For RM versus *gpΔR*, the inferred regression equation is $y = 40.1234 + 13.2988x$, where y is RM, and x is *gpΔR*. The linear correlation coefficient is $r = 0.8842$ (inferring that the inferred regression can explain about 78% of the variance in RM). The standard error of estimate $S_{yx} = 31.0150$, and the t-statistic equals 7.8980, inferring a confidence level cl >99.9%. The Kendall τ is computed to be $\tau_b = 0.7260$, and the Z-statistic is computed to be 4.9699 (inferring a probability P <0.0002). The

Fisher's exact test for the observed 2×2 contingency table (determined by the parametric medians – the horizontal and vertical lines) is computed to be $P_o = 0.0001$ and the probability of obtaining the observed result—or one more suggestive of a departure from independence (chance)—is likewise $P = 0.0001$. For RM versus ASC, the inferred association also is determined to be statistically important, as well. Hence, if SC25 has a rapid growth (and shorter ASC), clearly it would be expected to be a larger amplitude cycle (RM ≥184). On the other hand, if SC25 is a slow growing cycle (of longer ASC), it would be expected to be a smaller amplitude cycle (RM <184). (Note that fast-rising cycles also tend to be cycles of shorter PER (8 of 11 cycles), while slow-rising cycles tend to be cycles of longer PER (9 of 12 cycles). The numbered filled-circles denote the SC.)

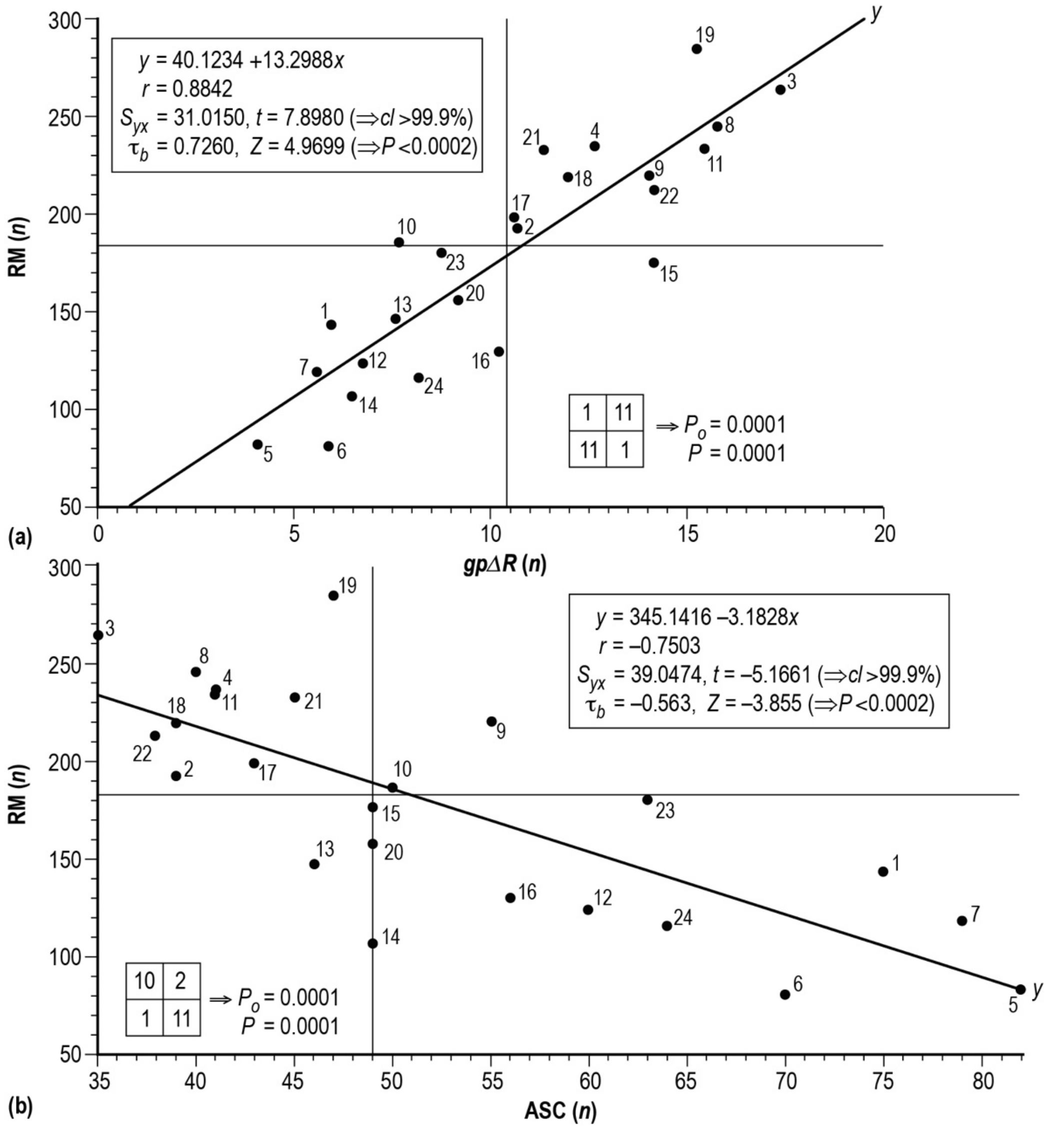

Figure 5. Scatterplots of RM (cycle *n*) versus (a) *gpΔR* (cycle *n*) and (b) ASC (cycle *n*).

Figure 6 displays scatterplots of PER versus (a) *gnΔR* and (b) RM for cycle *n*. As in Figure 5, the results of linear regression analysis and nonparametric analyses are given. The more statistically important association is that of PER versus *gnΔR*. Based on the observed value for SC24 (denoted by the arrow along the x-axis), one predicts using the inferred linear regression that PER = 141.1 ± 11.7 months for SC24, inferring that Em for SC25 should not be expected until on or after September 2019, probably near September 2020. Certainly, based on the observed 2 × 2 contingency table, one expects PER ≥135 months for SC24 (meaning Em for SC25 should not be expected until on or after March 2020).

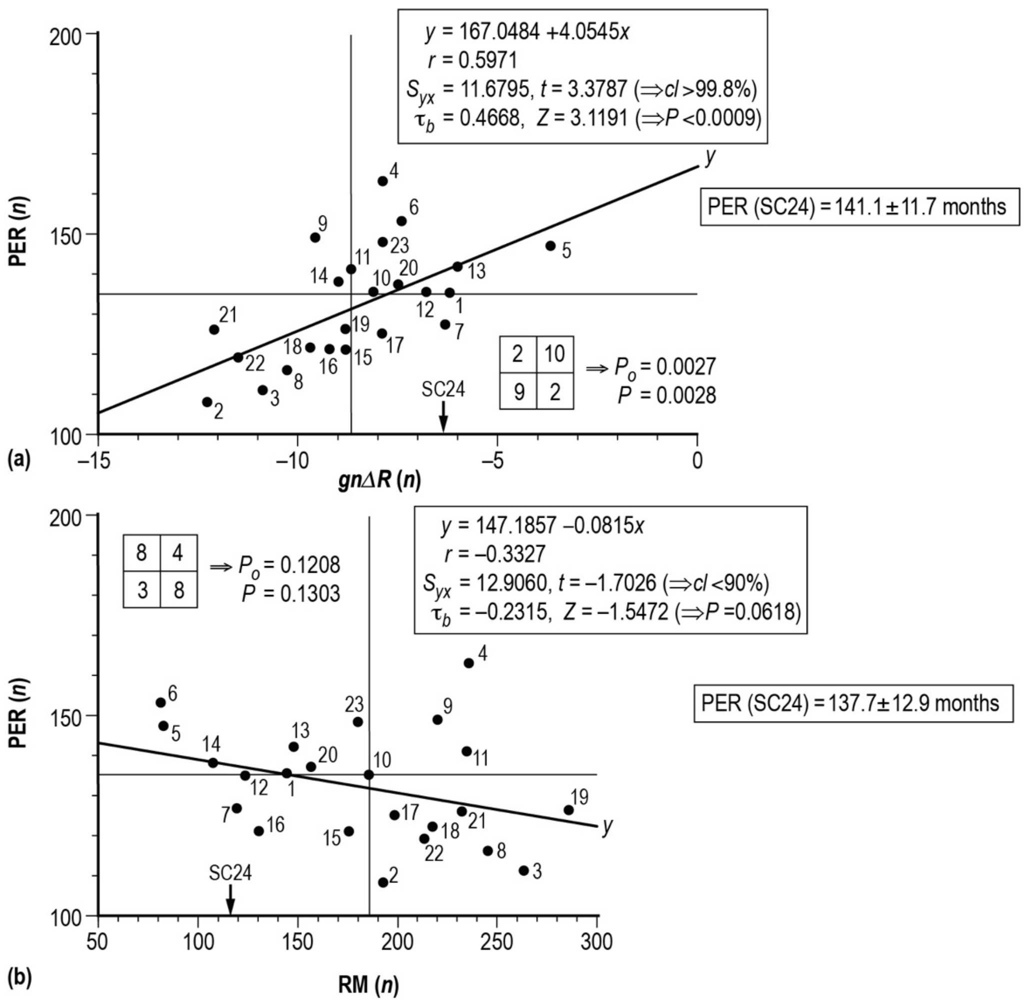

Figure 6. Scatterplots of PER (cycle *n*) versus (a) *gnΔR* (cycle *n*) and (b) RM (cycle *n*).

Figure 7 shows the scatterplot of SLOPE (DES) versus SLOPE (ASC). Based on the observed SLOPE (ASC) for SC24, one predicts that SLOPE (DES) = –1.5903 ± 0.3789 for SC24 using the inferred linear regression. Assuming SLOPE (DES) = –1.5903 for SC24 and that Rm = 0 for SC25, then one determines that DES = 73 months for SC24, yielding PER = 137 months for SC24 and that SC25's Em would be May 2020. Of course, the actual value for SLOPE (DES) will not be known until Rm for SC25 is known. (*R* = 6.0 in December 2018 and the trend is towards smaller *R*-values.)

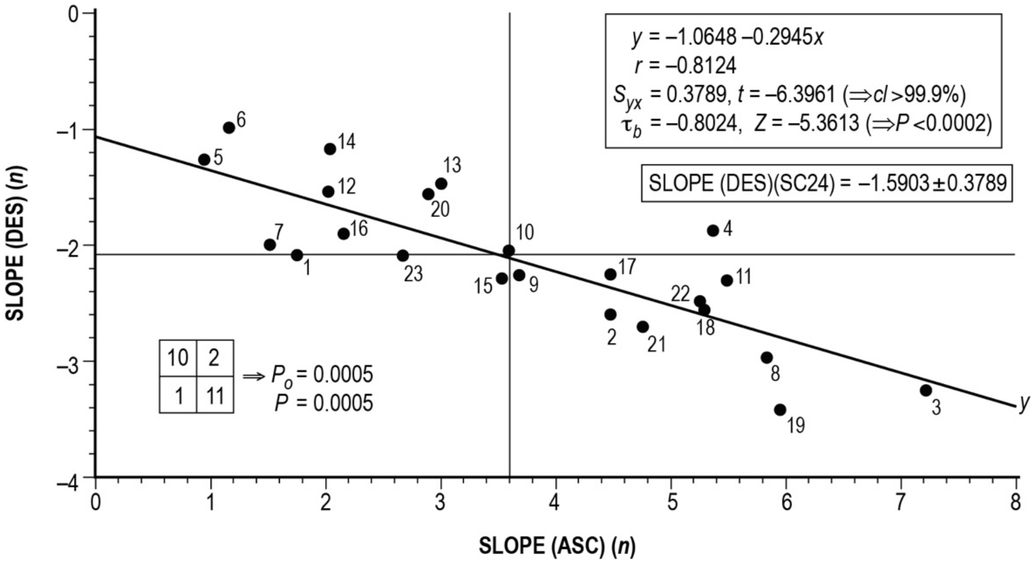

Figure 7. Scatterplot of SLOPE (DES) (cycle *n*) versus SLOPE (ASC) (cycle *n*).

Figure 8 displays (a) the scatterplot of Rm (n + 1) versus PER (n) and (b) the variation of R from May 2017 through December 2018. Regarding the scatterplot, both the linear regression analysis and nonparametric analyses indicate that the inferred association is statistically important. The R-value for December 2018 (= 6.0), which is elapsed time t = 120 months, is well below the median value of Rm (n + 1) = 9.4. For t = 120 months, one expects Rm (25) = 12.1 ± 4.7 based upon the inferred linear regression. Presuming SC24/25 is not a statistical outlier, an Rm value of 6.0 or below suggests that PER (24) likely will be ≥135 months, suggesting Em for SC25 on or after March 2020. If this is true, then the minimum interval for SC24/25 will be uncharacteristically long, as was the minimum interval between SC23/24 (cf. Russell, Luhmann and Jian 2010; Nandy, Muñoz-Jaramillo and Martens 2011). Using R = 10.0 as an arbitrary level for indicating the beginning and ending of a sunspot minimum interval, one finds that 10 of the intervals never dipped below the arbitrary threshold. These included cycle minimum intervals SC1/2, SC2/3, SC3/4, SC7/8, SC8/9, SC17/18, SC19/20, SC20/21, SC21/22, and SC22/23. Thirteen intervals, however, did cross below the threshold. These include SC4/5 (16 months), SC5/6 (44 months), SC6/7 (19 months), SC9/10 (11 months), SC10/11 (1 month), S11/12 (16 months), SC12/13 (11 months), SC13/14 (21 months), SC14/15 (34 months), SC15/16 (4 months), SC16/17 (7 months), SC18/19 (7 months) and SC23/24 (26 months). The time in months from crossing below the threshold to Em (n + 1) has spanned 1–26 months, averaging 10.2 ± 7.4 months. SC24 dipped below the threshold in March 2018, indicating that the duration of this arbitrary minimum interval will be ≥9 months. If the time between crossing below the threshold to Em (25) is similar to that of SC23/24 (= 17 months), then Em (25) would be expected about August 2019. However, if the time between crossing below the threshold and the Em is more like that for SC14/15 (= 26 months), then Em (25) should not be expected until May 2020. (SC24 has been compared to that of SC14; Wilson 2017.)

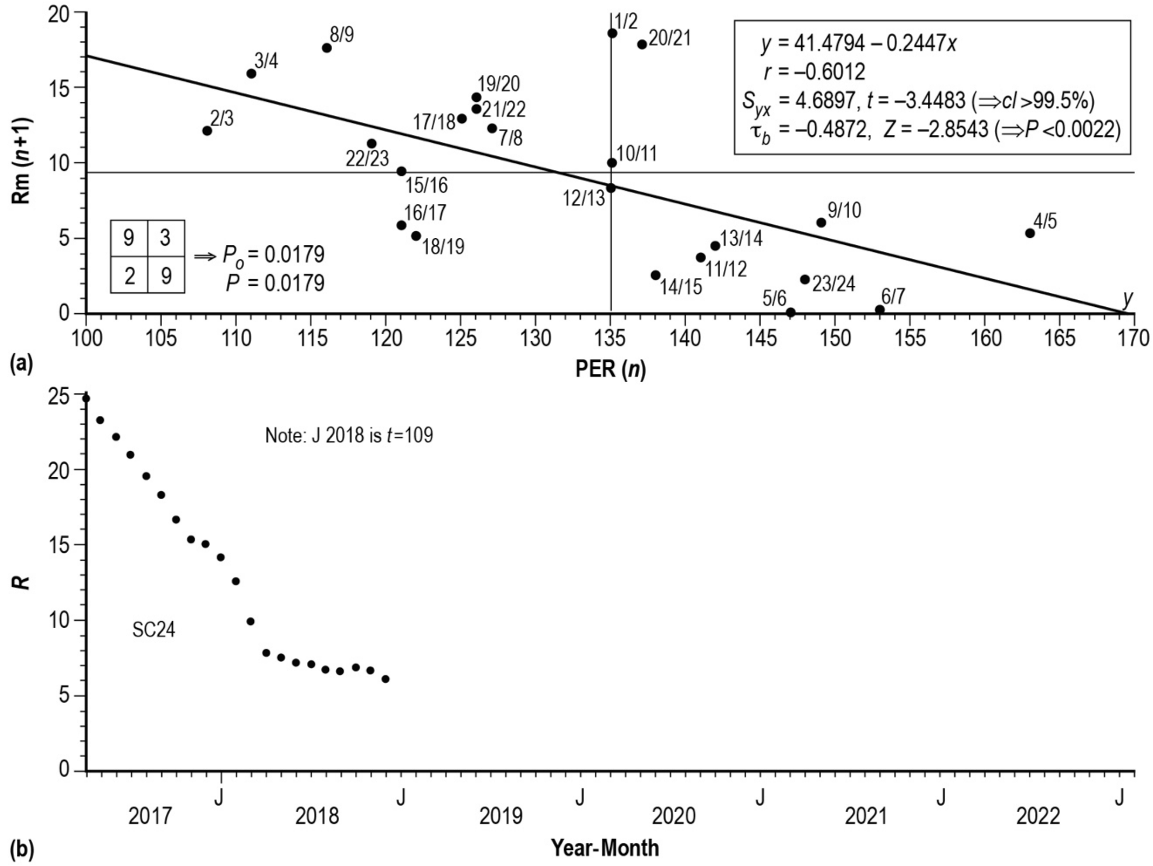

Figure 8. (a) Scatterplot Rm (cycle *n* + 1) versus PER (cycle *n*) and (b) variation of *R* for April 2017 through December 2018.

Figure 9 shows scatterplots of (a) RM (*n* + 1) versus PER (*n*) and (b) ASC (*n* + 1) versus PER (*n*). Of the two scatterplots, the former one is the more statistically important. In the scatterplot, notice the PER gap between PER = 127–135 months. Of the 23 SC of known PER that have been recorded, none have had a PER falling within this gap. Eleven have had PER = 108–127 months and 12 have had PER = 135–163 months. Hence, one suspects that PER (24) will be either ≤127 months or ≥135 months. Although *R*-values are known only through December 2018 (t = 120 months), monthly mean values of sunspot number are known through June 2019 (t = 126 months), with the first 6 months of 2019 having monthly mean sunspot number values of 7.7, 0.8, 9.4, 9.1, 10.1 and 1.2 (January–June). For July 2019, there have been only 2 days reported with nonzero daily sunspot number (July 7 (12) and July 22 (13)). Hence, a preliminary monthly mean value of 0.8 is estimated for July 2019, inferring R = 5.4 for January 2019, a decrease of 0.6 units of sunspot number from December 2018. Hence, it appears very likely that SC24 will have PER ≥ 135 months, suggesting Em for SC25 on or after March 2020, unless SC24 is a statistical outlier and becomes the first cycle to have a PER that falls within the gap. Presuming SC24 is indeed a longer-period cycle, one expects SC25 to be of smaller amplitude, with the SC24/25 dot falling in the lower right quadrant of Figure 9(a). Also, one would expect SC25 to be a slow rising cycle with ASC ≥49 months, with the SC24/25 dot falling in the upper right quadrant of Figure 9(b), meaning that EM for SC25 should occur on or after April 2024.

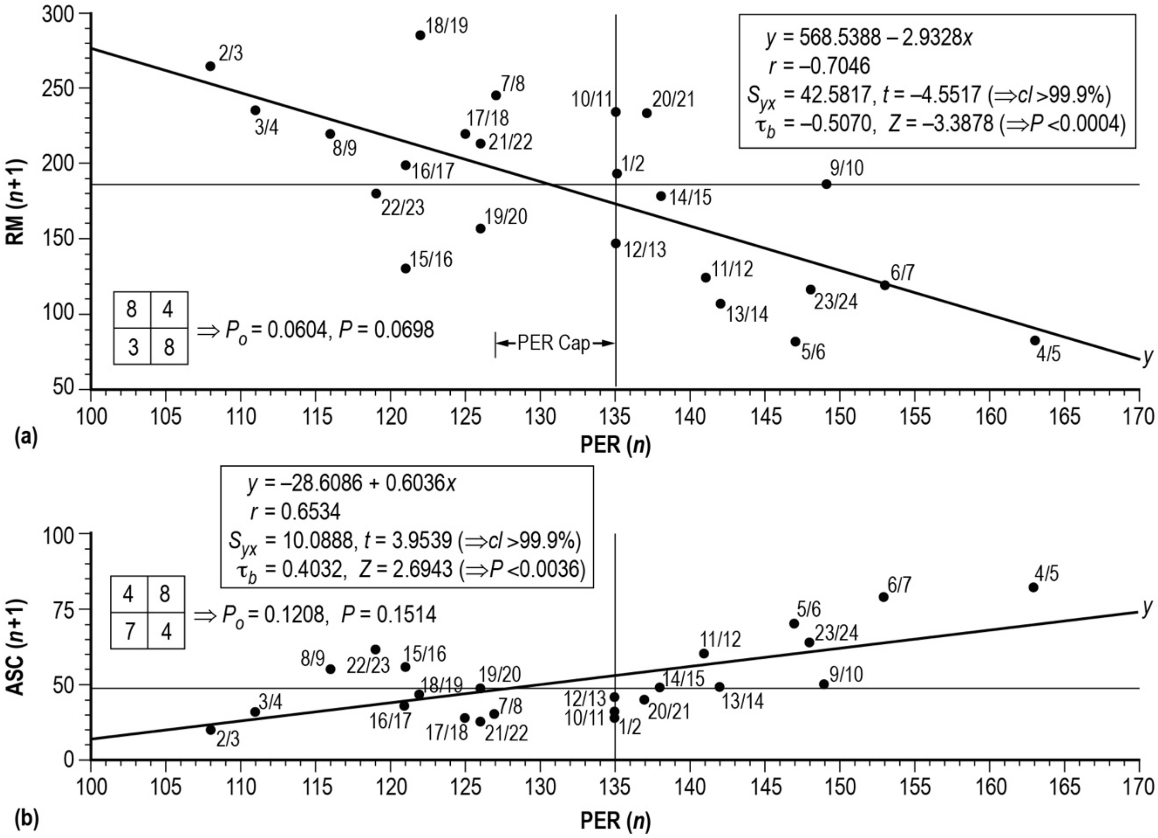

Figure 9. Scatterplots of (a) RM (cycle *n* + 1) versus PER (cycle *n*) and (b) ASC (cycle *n* + 1) versus PER (cycle *n*).

Figure 10 displays (a) the undifferentiated latitudinal (LAT) location of the spot groups on the Sun and (b) the number of spotless days (NSD) for the interval January 2018–June 2019. The lone dot at 32° is region 12694, observed January 9–11, 2018 (actually located at LAT = –32°), which was a magnetically simple old-cycle (i.e., SC24) spot of corrected small area (10 millionths of the solar hemisphere). Plainly, through June 2019, no high-latitude (i.e., ≥30°) new-cycle (SC25) spots have been observed, where new-cycle spots have positive leading magnetic field in the northern hemisphere and negative-leading magnetic field in the southern hemisphere in odd–numbered solar cycles. Typically, when the number of high-latitude new-cycle spots become more prevalent, Em for the new cycle is very close (cf. Harvey and White 1999). Hence, Em for SC25 remains in the future, probably occurring in 2020 or later. Regarding NSD, there were 208 spotless days in 2018 and 107 for the first half of 2019 (136 through July 2019). (NSD peaks in the year of sunspot minimum based on annual sunspot number; Wilson 2017.)

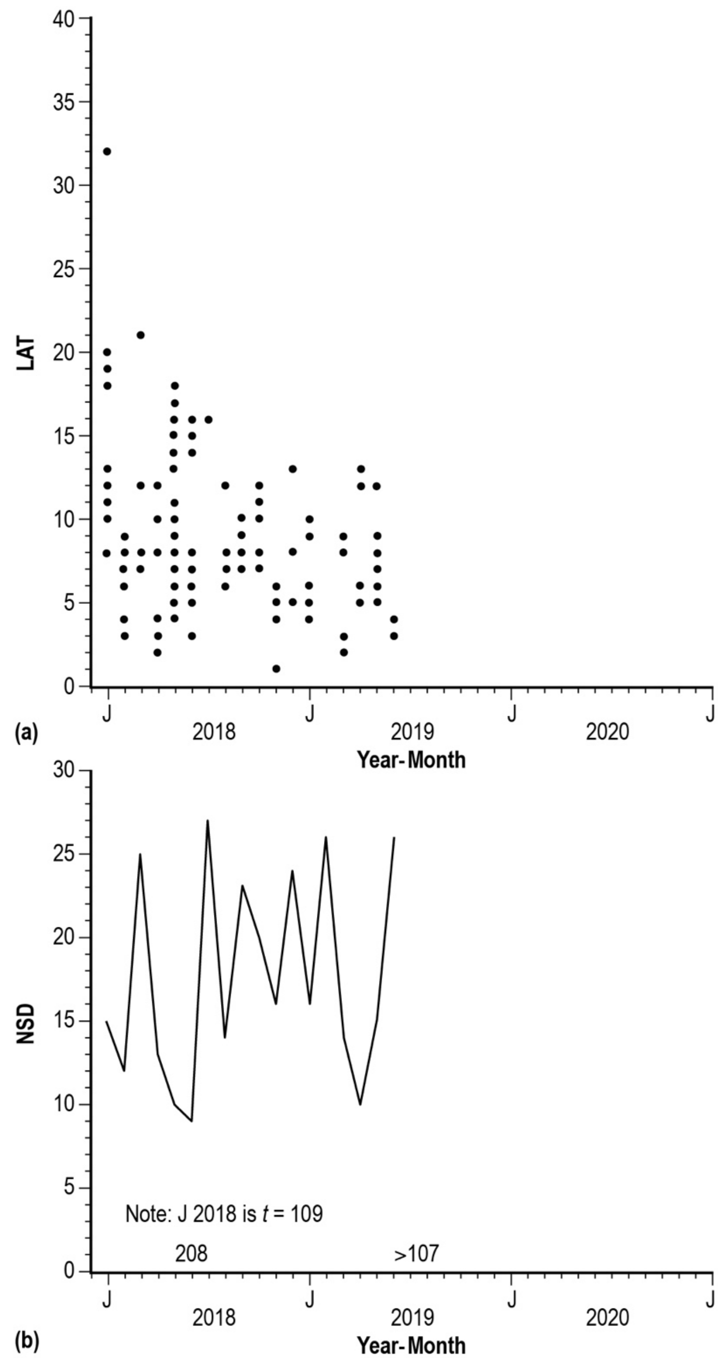

Figure 10. (a) Variation of undifferentiated spot latitude (LAT) for January 2018 through June 2019 and (b) variation of number of spotless days (NSD) for January 2018 through June 2019.

In conclusion, Em for SC25 is close but not really expected until probably March 2020 or later. Hence, the relatively low *R*-values experienced throughout 2018 likely will continue through 2019 and into 2020. This portends another uncharacteristically long minimum interval for SC24/25 like that experienced for SC23/24. Therefore, SC24 is projected to be a cycle of longer PER (≥135 months), meaning that Em for SC25 should not be expected until March 2020 or later. If true, then one expects SC25 to be a cycle of smaller amplitude (RM < 184) and a slow riser (ASC ≥ 49 months), inferring EM for SC25 in 2024 or later. Also, assuming SC25 is not a statistical outlier, its RM should be larger than 116.4 (the RM for SC24), based on the even-odd effect (i.e., odd-numbered SCs typically have been the larger cycle in even-odd SC pairs, true for 8 of 12 cycle pairs for SC0–SC23; cf. Wilson 2018).

LITERATURE CITED

Clette, F., L. Svalgaard, J. M. Vaquero, and E. W. Cliver 2015. Revisiting the Sunspot Number: A 400-Year Perspective on the Solar Cycle, *Space Sciences Series of ISSI 53, The Solar Activity Cycle: Physical Causes and Consequences*, A. Balogh, H. Hudson, K. Petrovay, and R. Von Steiger (eds.), Springer-Verlag, New York, pp. 35–103.

Clilverd, M. A., E. Clarke, H. Rishbeth, T. D. G. Clark, and T. Ulich 2003. Solar Activity Levels in 2100 *Astron. & Geophys.*, 44(5), pp. 5.20–5.22, doi:10.1046/j.14684004.2003.44520.x.

Everitt, B. S. 1977. *The Analysis of Contingency Tables*. Chapman and Hall, London, p. 15.

Gibbons, J. D. 1993. *Nonparametric Measures of Association*, Series Number 07-091: Sage Publ., London, D. S. Foster (ed.), p. 3.

Hathaway, D. H. 2008. Solar Cycle Forecasting, *Space Sci. Rev.*, 144(1–4), pp. 401–412.

Hathaway, D. H. 2015. The Solar Cycle, *Living Reviews Solar Physics* 12(4), 87 pp., doi:10.1007/Irsp-2015-4.

Hathaway, D. H., R. M. Wilson, and E. J. Reichmann 1999. A Synthesis of Solar Cycle Prediction Techniques, *J. Geophys. Res.*, 104(A10), pp. 22,375–22,388.

Harvey, K. L. and O. R. White 1999. What Is Solar Cycle Minimum? J. Geophys. Res., 104(A9), pp. 19,759–19,764.

Nandy, D., A. Muñoz-Jaramillo, and C. H. Martens 2011. The Unusual Minimum of Sunspot Cycle 23 Caused by Meridional Plasma Flow Variations, *Nature*, 471, pp. 80–82.

Pesnell, W. D. 2012. Solar Cycle Predictions, *Solar Phys.*, 281, pp. 507–532.

Petrovay, K. 2010. Solar Cycle Prediction, *Living Reviews Solar Physics* 7(6), 94 pp, doi:10.122942/Irsp-2010-6.

Russell, C. T., J. G. Luhmann and L. K. Jian 2010. How Unprecedented a Solar Minimum? *Rev Geophys.*, 48(2), 36 pp., doi: 10.1029/2009RG000316.

Song, P., H. J. Singer, and G. L. Siscoe (eds.) 2001. *Space Weather125*, American Geophysical Union, Washington, DC, 440 pp.

Svalgaard, L., E. W. Cliver, and Y. Kamide 2005. Sunspot Cycle 24: Smallest Cycle in 100 Years? *Geophys. Res. Lett.*, 32(1), 14 pp., doi:10.1029/2004GL021664.

Uzal, L. C., R. D. Piacentini and P. F. Verdes 2012. Predictions of the Maximum Amplitude, Time of Occurrence, and Total Length of Solar Cycle 24, *Solar Phys.*, 279(2), pp. 551–560.

Wilson, R. M. 2015. Sunspot Cycle Characteristics based on the Newly Revised Sunspot Number, *Journal of the Alabama Academy of Science*, 86(3/4), pp. 203–221.

Wilson, R. M. 2017. Number of Spotless Days in Relation to the Timing and Size of Sunspot Cycle Minimum, *Journal of the Alabama Academy of Science*, 88(2) pp. 96–120.

Wilson, R. M. 2018. An Examination of the Sunspot Areal Dataset, 1875–2017: Paper I, An Overview, *Journal of the Alabama Academy of Science*, 89(2), in press.

Withbroe, G. L. 1989. Solar Activity Cycle: History and Predictions, *J. Spacecraft*, 26, pp. 394–402.