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An Improved Solar Cycle Statistical Model for the Projection of Near Future Sunspot Cycles

Myung-Hee Y. Kim,[1,2] John W. Wilson,[3] Francis A. Cucinotta[2]
[1]Wyle Laboratories
Houston, Texas
[2]Johnson Space Center
Houston, Texas
[3]Langley Research Center
Hampton, Virginia

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Abstract

Since the current solar cycle 23 has progressed near the end of the cycle and accurate solar minimum and maximum occurrences have been defined, a statistical model based on the odd-even behavior of historical sunspot cycles was reexamined. Separate calculations of activity levels were made for the rising and declining phases in solar cycle 23, which resulted in improved projection of sunspots in the remainder of cycle 23. Because a fundamental understanding of the transition from cycle to cycle has not been developed, at this time it is assumed for projection purposes that solar cycle 24 will continue at the same activity level in the declining phase of cycle 23. Projection errors in solar cycle 24 can be corrected as the cycle progresses and observations become available because this model is shown to be self-correcting.

Introduction

Accurate predictions of radiation dose to astronauts on board the International Space Station in future years are needed for mission planning. Limitations in crew return vehicles and the more stringent dose limits recently implemented by NASA (ref. 1) suggest that mission duration and altitude could be important constraints on the selection of younger astronauts or those who have been involved in previous long-duration missions, especially near solar minimum. A statistical model based on the accumulating cycle sunspot data was developed to estimate future levels of solar cycle activity, and since the sunspot cycles affects the near-Earth environment, the data were coupled to space-related quantities of interest in radiation protection (ref. 2). As solar cycle 23 progressed and the beginning of cycle 23 was well defined, this model was evaluated by examining the measured data with the prediction, in which the measured data were within the confidence interval of the analysis made with only the first nine months of cycle 23 (ref. 3). At that time, a new prediction was made with 47 observed data of monthly mean values of sunspot numbers after May 1996 (ref. 3). As cycle 23 is nearing its end, the beginning and the maximum of the cycle were accurately adjusted as May 1996 and April 2000, respectively (ref. 4). In the present report, this model is reexamined to improve sunspot prediction for the latter part of the cycle and beyond.

Critical parameters in cycle prediction include not only the date of solar minimum occurrence but also the date of solar maximum occurrence in each cycle. It has been shown that the sunspot number randomizes through the remainder of the declining phase of the cycle when only a difference between even and odd cycles was treated as two independent populations (ref. 2 and 3). When the rising and declining phases of each cycle are also treated as two independent populations within the relevant even/odd cycle, the activity level in the latter part of each cycle was found to be consistent for all of the historical sunspot data, where it was previously considered as being randomized.

A new mean cycle level for the latter part of cycle 23 was generated with an adjusted solar maximum of April 2000 and with the measured sunspot data for 43 months after the solar maximum. The previous prediction of sunspot cycle parameter to the end of cycle

23 is unchanged, because good correlation with smaller statistical fluctuations was found between cycle duration and the activity level in rising phase of the cycle (refs. 2 and 3). Because a fundamental understanding of the transition from cycle to cycle is not yet developed, the mean cycle levels in the declining phase of solar cycle 23 were used for the projection into the next cycle and to predict the time to the next solar maximum. The resultant cycle prediction will be coupled to space-related quantities of interest in radiation protection.

Mean and Statistical Fluctuation of Sunspot Data of Cycle 23

Currently, there are 90 observed data of monthly averaged sunspot numbers for solar cycle 23 (ref. 4). To calculate the percentile levels of the sample data, an appropriate population distribution for each successive month was generated from the historical sunspot numbers for odd cycles and the associated cumulative frequency spectrum was generated (refs. 2 and 3). The percentile levels for each month from the cycle 23 minimum were calculated by interpolation/extrapolation of each sunspot number with the associated cumulative frequency spectrum. At the beginning of the present solar cycle 23, the monthly averaged sunspot number in May 1996 is on the 91-percentile level of sunspot numbers at previous solar minima in odd cycles. As the sample size increased each month, cumulative mean percentile level and statistical fluctuations of the sample data were calculated for the range of percentile groups. This calculation, illustrated in figure 1, clearly shows that the uncertainty in mean percentile grouping is contracting with expanding current data until reaching the solar maximum (the monthly index number of 48 in figure 1). After passing solar maximum, solar activity becomes chaotic, resulting in greater statistical fluctuation in declining phase, as shown in figure 1. When the sample sunspot number populations are separated into rising and declining phases, a more meaningful and consistent trend is observed, as shown in figures 2a and 2b. Figure 2a is for the first 56 months of solar cycle 23, from the beginning of the cycle up to eight months after solar maximum. As the cycle proceeds toward solar maximum, the mean percentile grouping in the rising phase of the current cycle is 66 percentile with a standard deviation of 16 percent, which remains unchanged from the previous prediction from a sample of 47 data size (ref. 3).

In figure 2b the remaining cycle starts from solar maximum. The monthly sunspot number in April 2000 is in the 64-percentile level of sunspot numbers at previous solar maxima in odd cycles. After some chaotic behavior, the declining phase of this cycle is contained to a mean of 75 percentile, with a standard deviation of 16 percent. From this mean and standard deviation of the sample size 43 of a normal population, the mean activity level in the entire declining phase of cycle 23 would be at 75 percent $\pm$ 5 percent with 42 degrees of freedom and with a 95-percent confidence interval.

Population Distribution in the Declining Phase After Solar Maximum for All Even/Odd Cycles

In the previous report (figures 1 and 2 in ref. 3), the historical sunspot number distributions, along with the associated population distributions of 10-, 30-, 50-, 70-, 90-, and 100-percent levels, were compared for 11 separate odd and even cycles as each cycle progresses from its solar maximum. This comparison concluded that all of the historical sunspot cycles are reasonably consistent with each activity level during the rising phase, while they randomize through the remainder of the cycle. This can be attributed to the fact that the succeeding solar minimum was not correlated with prior cycle maximum, as seen in figure 3. This randomization tendency disappears when the distribution of solar cycle in declining phase is treated independently from that of the rising phase. These distributions of sunspot numbers in declining phases of all 11 historical odd-even cycles are shown in figure 4 for odd cycles and in figure 5 for even cycles along with the associated population distributions of 10-, 30-, 50-, 70-, 90-, and 100-percent levels. In these figures, the declining phase of each progresses from its solar maximum and shows that there is still randomization near the cycle end. However, this randomization is mainly originated from using the same data size (the length) in the declining phase for each cycle. In fact, the duration of cycle in declining phase varies from 66 months to 122 months as shown in table 1. Therefore, the obvious increase in sunspot numbers in some cycles and in distribution levels towards the cycle end are caused simply by the extension of the monthly index into the next solar cycle from the relatively short cycle while accumulating the even/odd historical sunspot data. When the length of individual cycle is considered, this increase will disappear and consistent activity levels are seen for all of the historical sunspot cycles in figures 4 and 5. As shown in figure 4f, the distribution in declining phase of solar cycle 23 appears to be running its course with a consistent activity level after shifting from a lower activity level in rising phase. This indicates that the remainder of cycle 23 will be at 75 percent ± 5 percent of the historical populations in declining phases of odd cycles, despite the chaotic activity observed for a while after the solar maximum.

Sampling Distribution and New Projection of Cycle 23 and Beyond

The solar cycle projection for the remainder of this cycle is made, as shown in figure 6a, at the activity levels obtained from the statistically independent pattern of declining phase from that of rising phase. The 13-month running average sunspot numbers and monthly values of the observations are also shown in figure 6a with the associated population distributions of 10-, 30-, 50-, 70-, and 90-percent levels in rising and declining phases of odd cycles. The duration of cycle 23 was estimated from the correlation to the percentile group in rising period of the cycle. This remains unchanged from previous predictions at 10.6-years duration, as the same percentile groups in the rising period were obtained from the previous analysis (ref. 3). To avoid the obvious misleading occurrence near the cycle end shown in figure 6a, the length between a solar maximum and the next solar minimum (in table 1) is considered for each cycle and corrections are shown in figure 6b. As the solar cycle nears its end, the historical data considered for the statistical calculation are

limited by excluding data that extend into the next cycle. In figure 6b, the associated distributions of various percent levels at the end of cycle are improved from this modification. However, the projection at the end of the cycle is still uncertain due to the dependence on the adjustment of solar minimum 24 and because less data from previous odd cycles are available for the interpolation/extrapolation.

Projections into the next cycle are difficult because they introduce uncertainty not only in the future amplitude, but also reflect uncertainty in the cycle duration (ref. 5). The lowest sunspot number index for solar cycle 24 cannot be determined precisely until well into cycle 24. This is assumed to occur in December 2006, based on the behavior of the odd-even solar cycles (refs. 2 and 3). The appropriate percentile grouping of cycle 24 cannot be made at present, since there is no correct adjustment of solar minimum for cycle 24 and no correlation between odd-even cycles (refs. 6 and 7). At best, the current progressive trend is assumed to continue into the next cycle for projection purpose only.

Using the current progressive trend, the new estimate of the time to the next solar maximum is shown in figure 7. Hence, the next solar maximum is currently projected to be in November 2010, with an uncertainty of 13 months. Once again, estimates of the next solar maximum and the corresponding sunspot number are uncertain because they are made based on the assumed minimum in December 2006 and the assumed progressive trends at 75 percent ± 5 percent. These errors are self-correcting as cycle observations become available.

Projection into the next cycle was generated with the statistical prediction parameters of solar minimum and maximum, as well as the assumed progressive trends, and is shown in figure 8 as a continuation from solar cycle 23. The mean cycle level of the entire cycle 24 is assumed to be at 75 percent ± 5 percent in rising and declining phases as shown in figure 8, in which estimates are shown along with historical sunspot levels of all even cycles in two separate phases. Here, the corresponding annual averaged maximum sunspot number is expected to be 122, with an uncertainty of 6. The estimates of cycle 24 minimum and maximum values are given in table 2.

Concluding Remarks

A previously developed statistical model for predicting solar cycle variations had been improved by separating the sample populations into rising and declining phases of each cycle and considering the different cycle length for accumulating historical sunspot data. As cycle 23 progresses with 90 available observed sunspot numbers, two separate activity levels in rising and declining phases of the cycle were obtained and a convergence toward improved estimates in the remainder of the cycle was achieved. From the sample of size 43 in the declining phase of the current cycle, the mean activity level of the remainder of cycle 23 would be at 75 percent ± 5 percent with 42 degrees of freedom and with a 95-percent confidence interval. Problems in cycle projection from one cycle to the next still exist due to a randomization process at the end of each cycle; the continued activity level is therefore assumed, and the solar minimum and solar maximum of cycle 24 are

estimated for projection purpose only. The projections of solar cycles into next cycle are made with the statistical predictions of cycle parameters. The corresponding averaged monthly minimum sunspot number and the next maximum sunspot number were also predicted. The current projection provides a basis for estimating exposures in future missions on the International Space Station or other spacecraft, despite the effect of uncertainties of solar cycle predictions existing on future shield design. Further study in a dynamic model based on some yet unidentified observable factor will allow more reliable predictions of successive cycle dependence.

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Table 1. The Duration of Cycle in Declining Phase (the Solar Maximum to the Next Solar Minimum)

Odd Cycles		Even Cycles	
Cycle Number	Duration, months	Cycle Number	Duration, months
1	57	2	68
3	69	4	122
5	72	6	78
7	47	8	78
9	93	10	84
11	94	12	66
13	94	14	82
15	66	16	66
17	76	18	73
19	81	20	84
21	72	22	78
23	80		

Table 2. Statistical Prediction of Sunspot Cycle Parameters

Parameter	Low end range		Average		High end range	
	Date	Sunspot number	Date	Sunspot number	Date	Sunspot number
Smoothed cycle 24 minimum	Feb. 2008	24	Dec. 2006	25	Dec. 2005	27
Smoothed cycle 24 maximum	May 2011	116	Nov. 2010	122	Apr. 2010	128

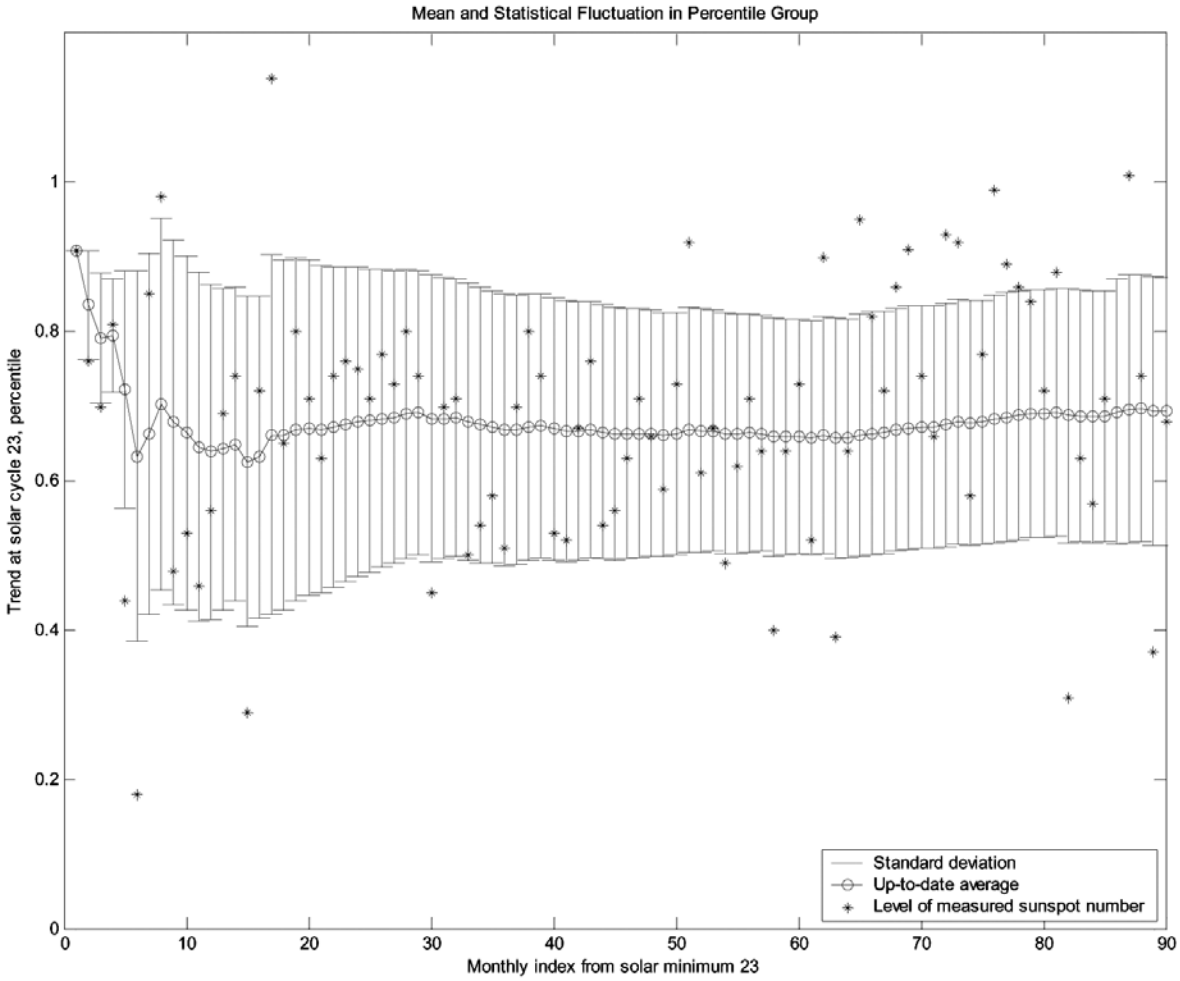


Figure 1. Percentile group of 90 months of cycle 23 and cumulative mean value and statistical fluctuation.

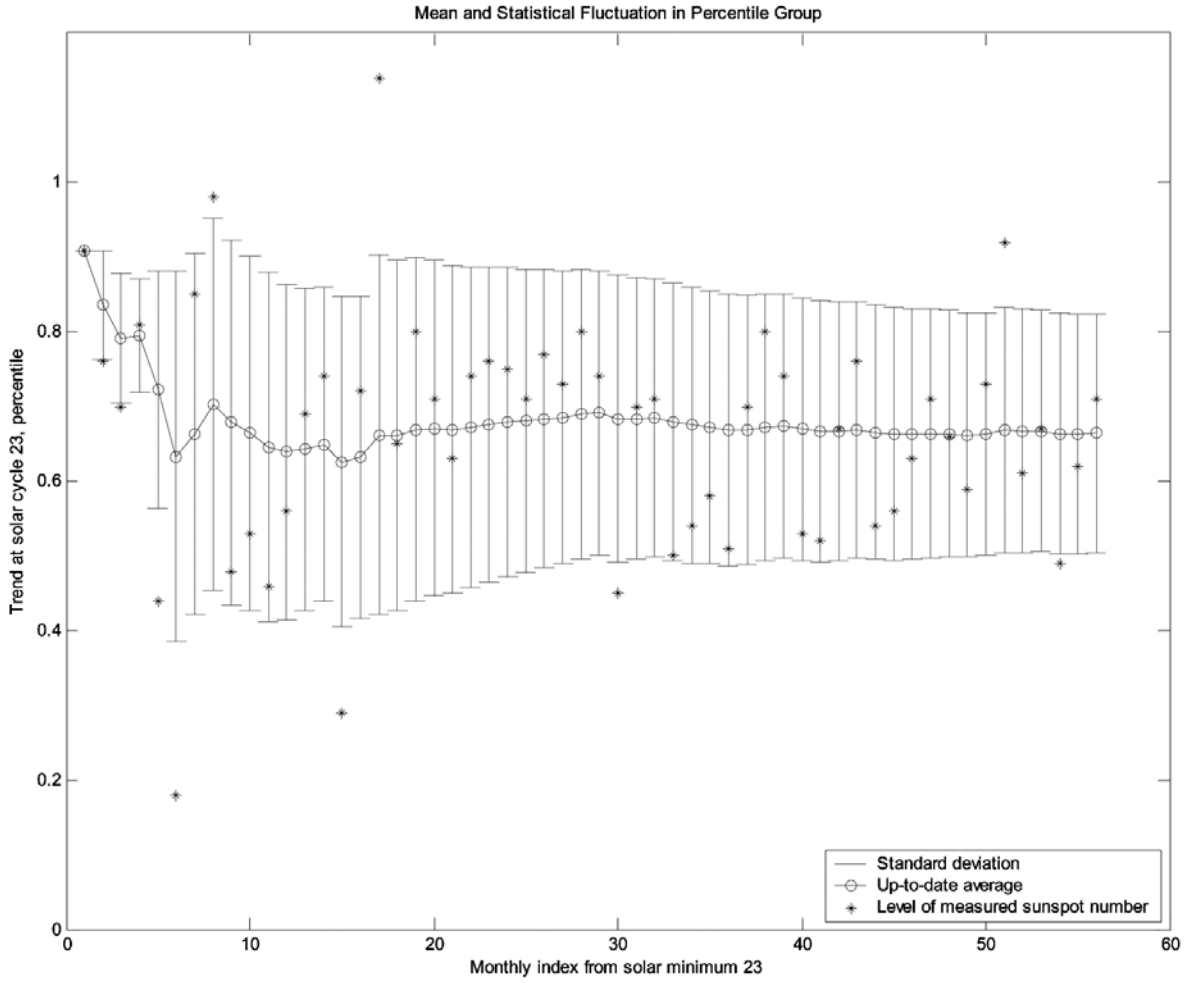


Figure 2a. Percentile group of first 56 months in the rising phase of cycle 23 and cumulative mean value and statistical fluctuation.

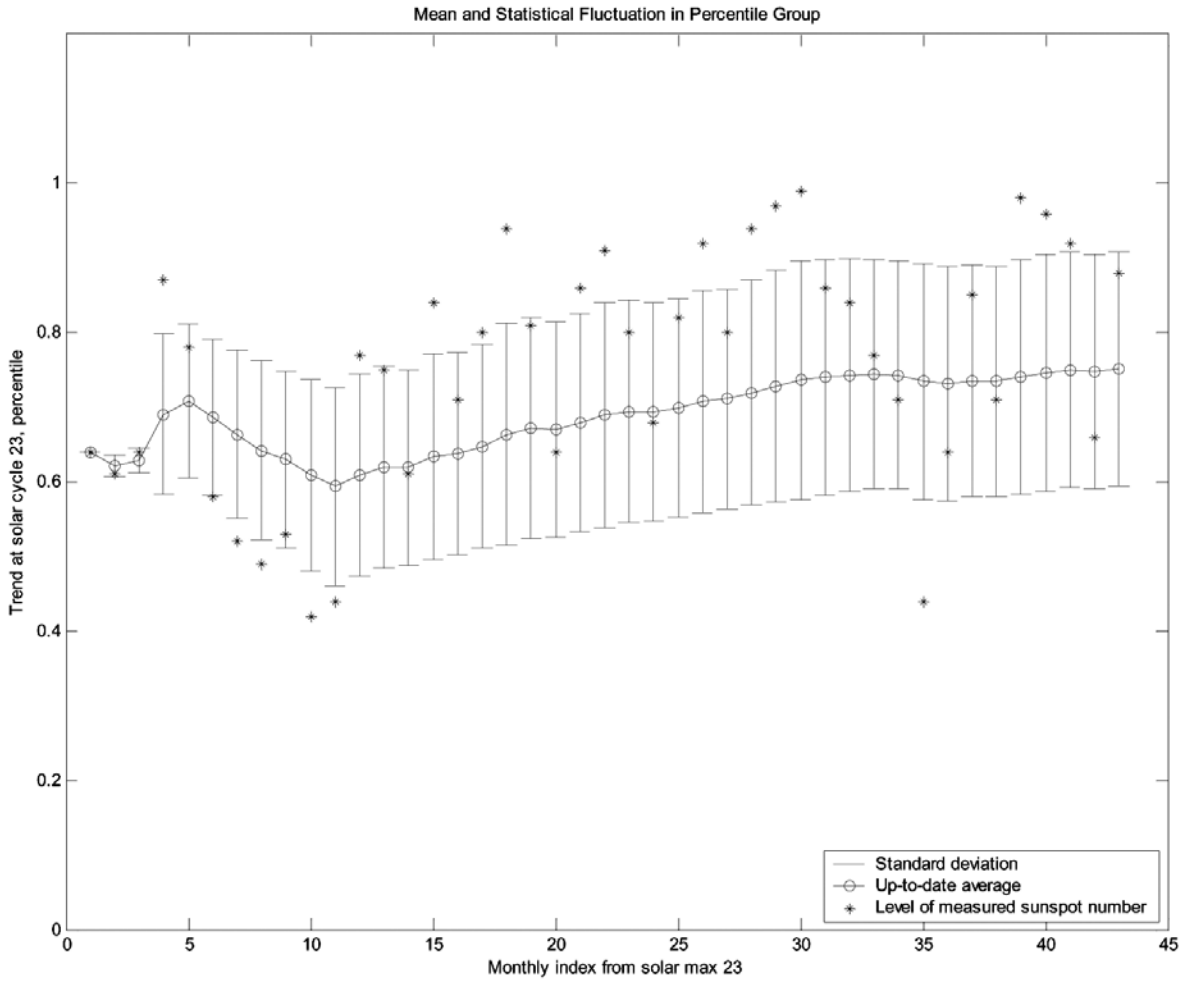


Figure 2b. Percentile group of 43 months in the declining phase of cycle 23 starting from the solar maximum and cumulative mean value and statistical fluctuation.

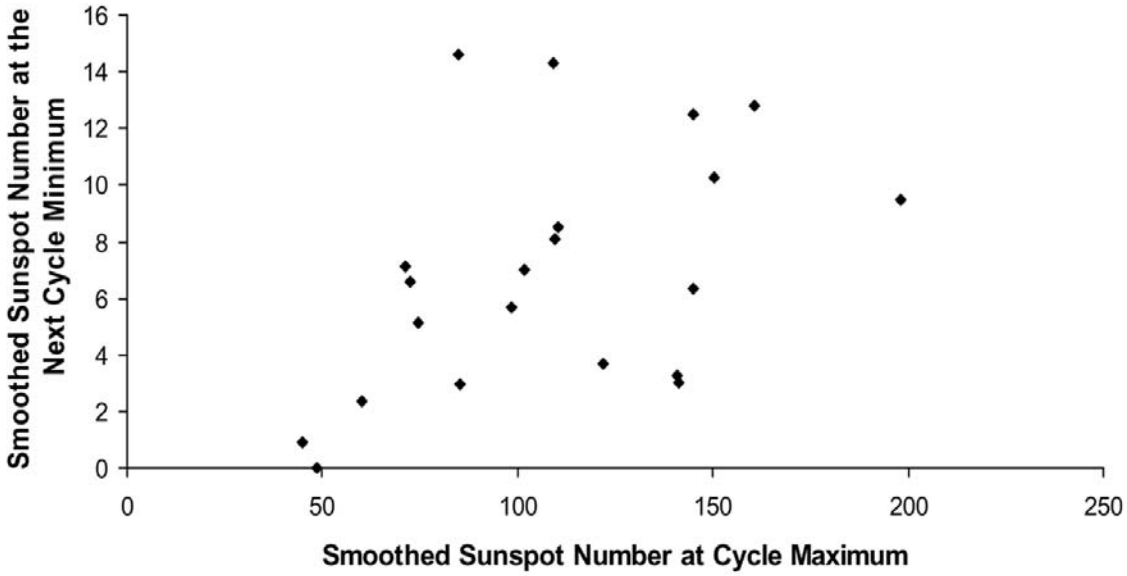
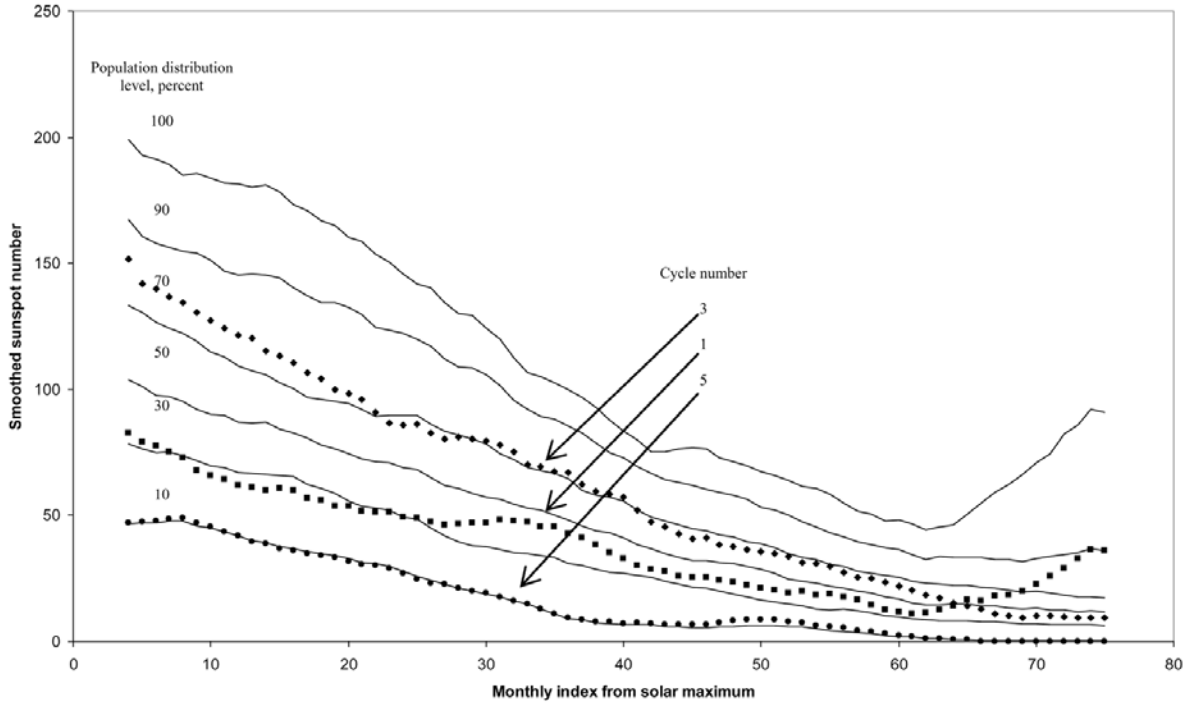
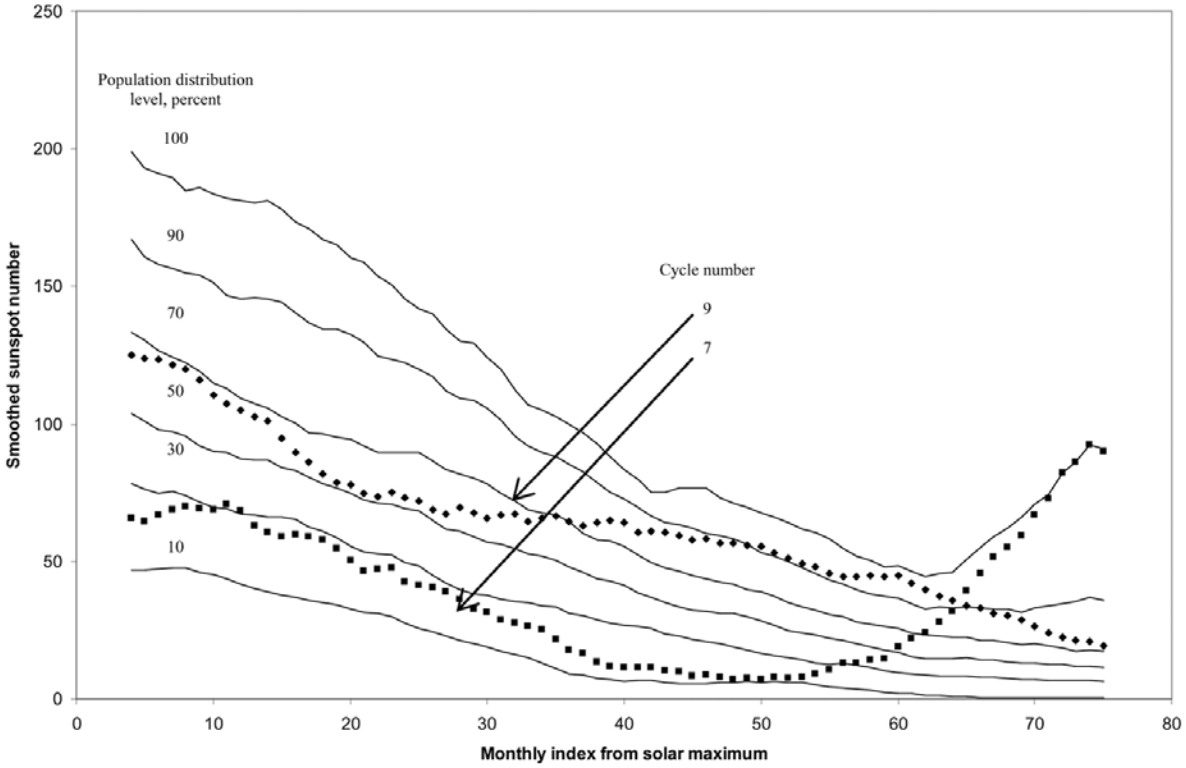


Figure 3. Scatter graph comparing smoothed minima of next cycle with prior cycle maxima showing no correlation between cycles.

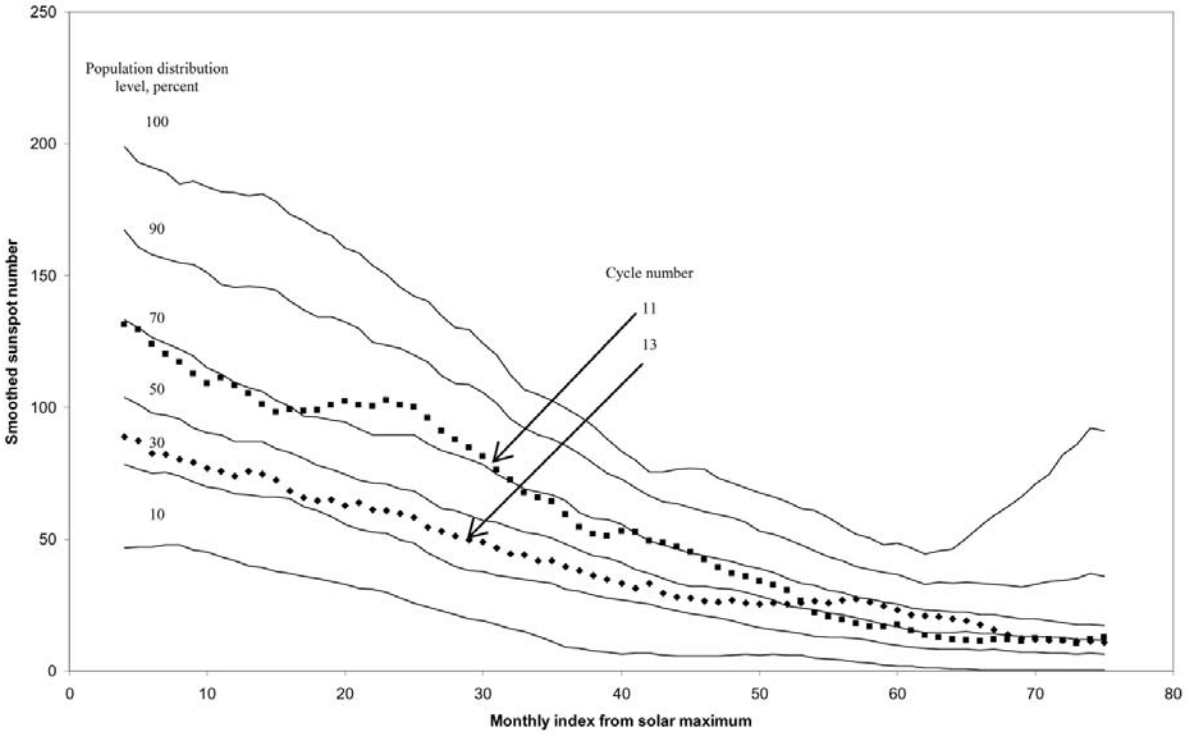


(a) Cycles 1,3, and 5

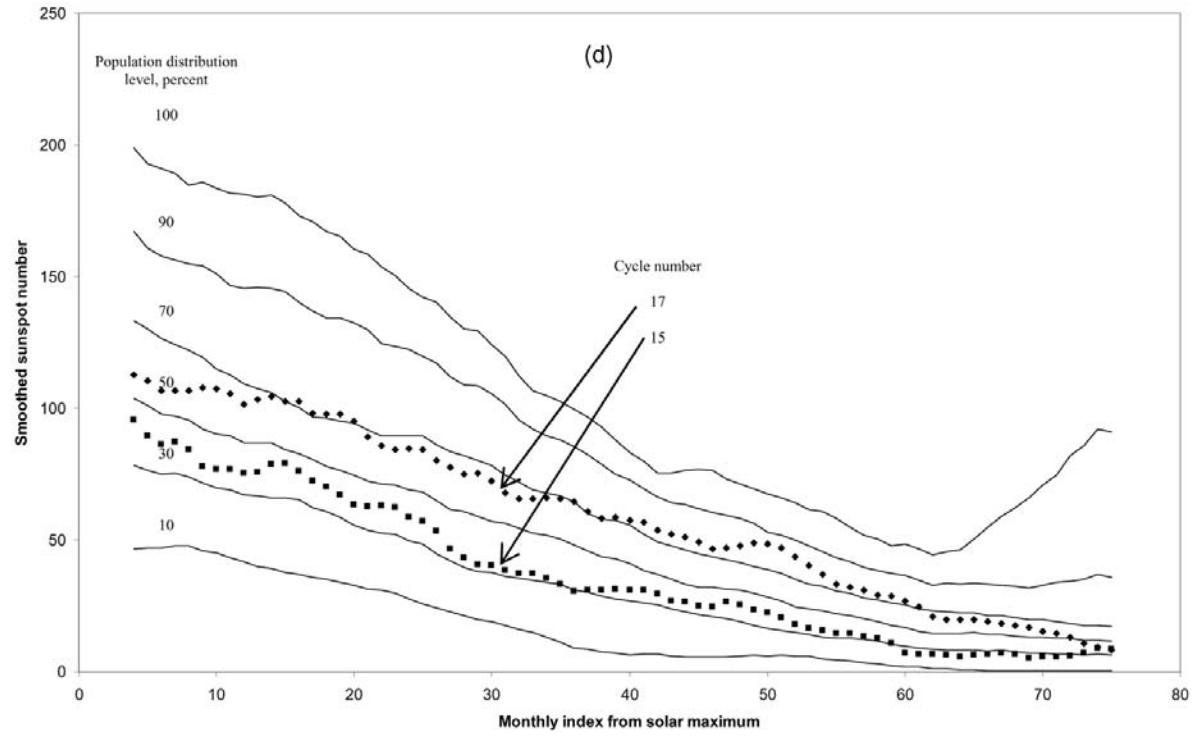


(b) Cycles 7 and 9

Figure 4. Historical sunspot number distribution in declining phase for odd cycles.

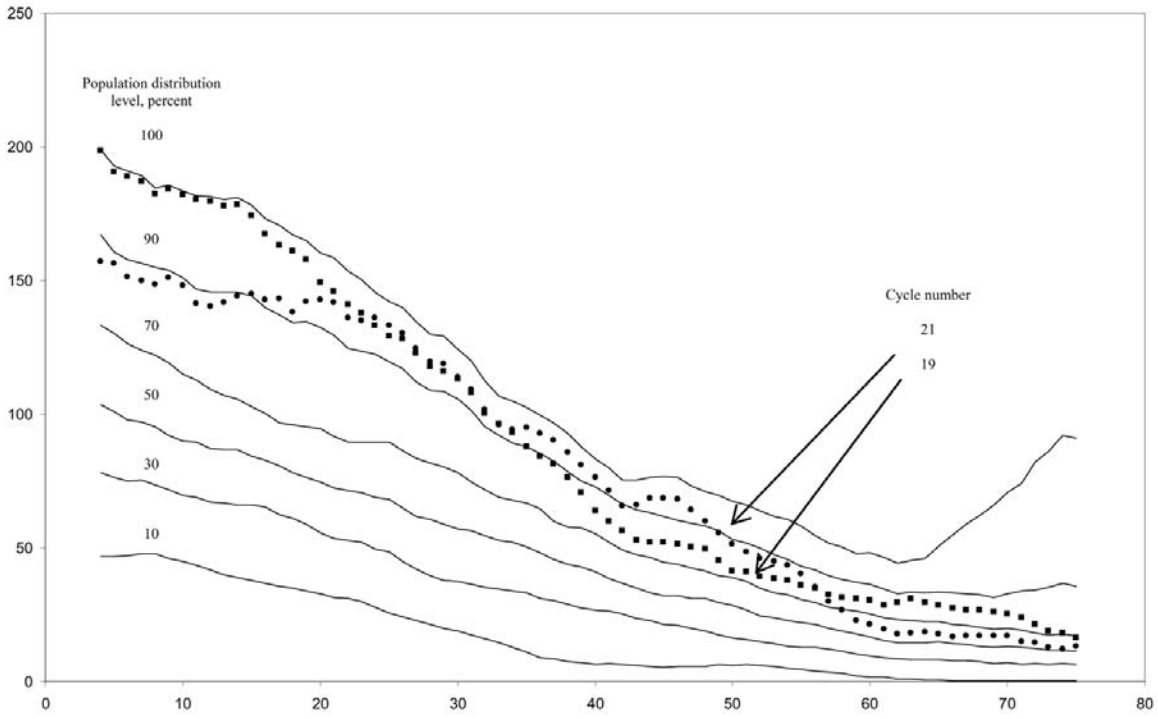


(c) Cycles 11 and 13

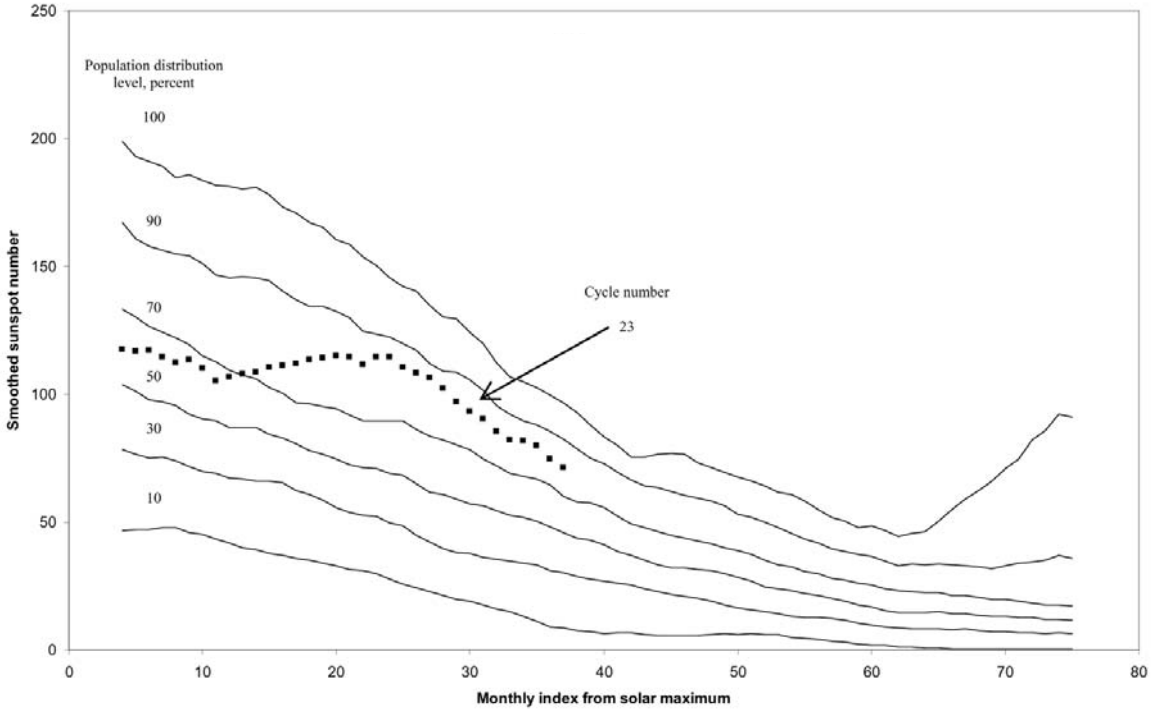


(d) Cycles 15 and 17

Figure 4. Continued.

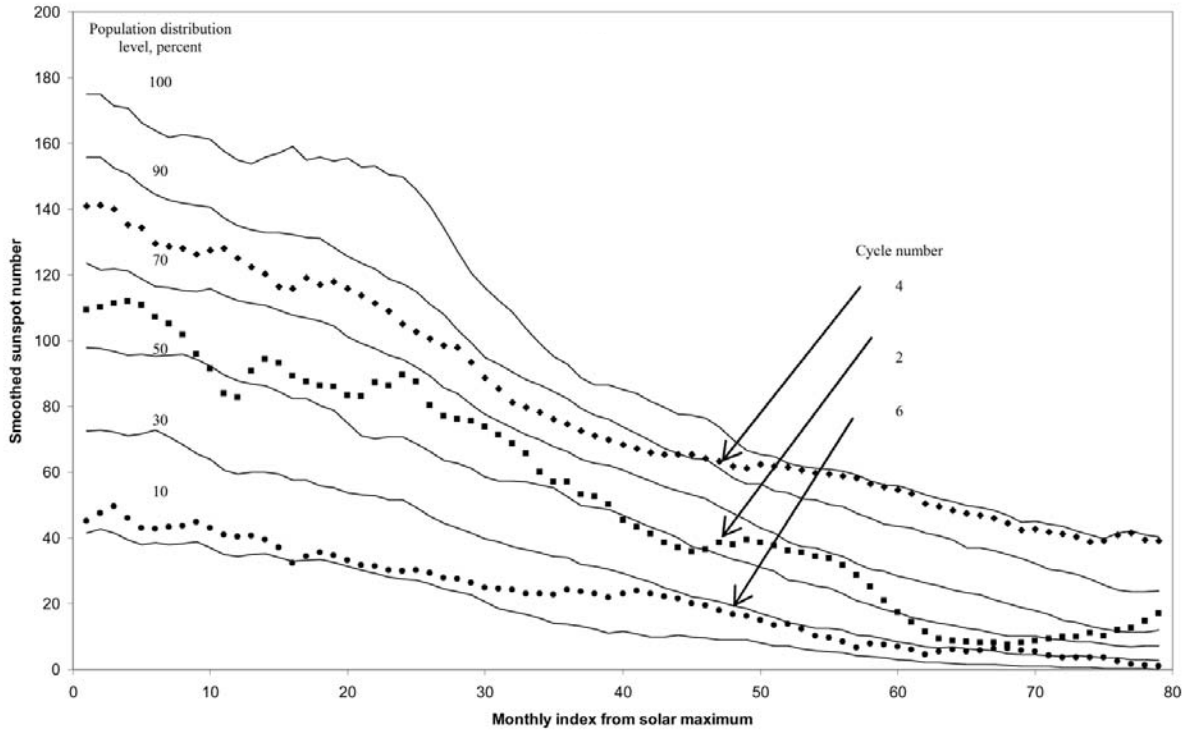


(e) Cycles 19 and 21

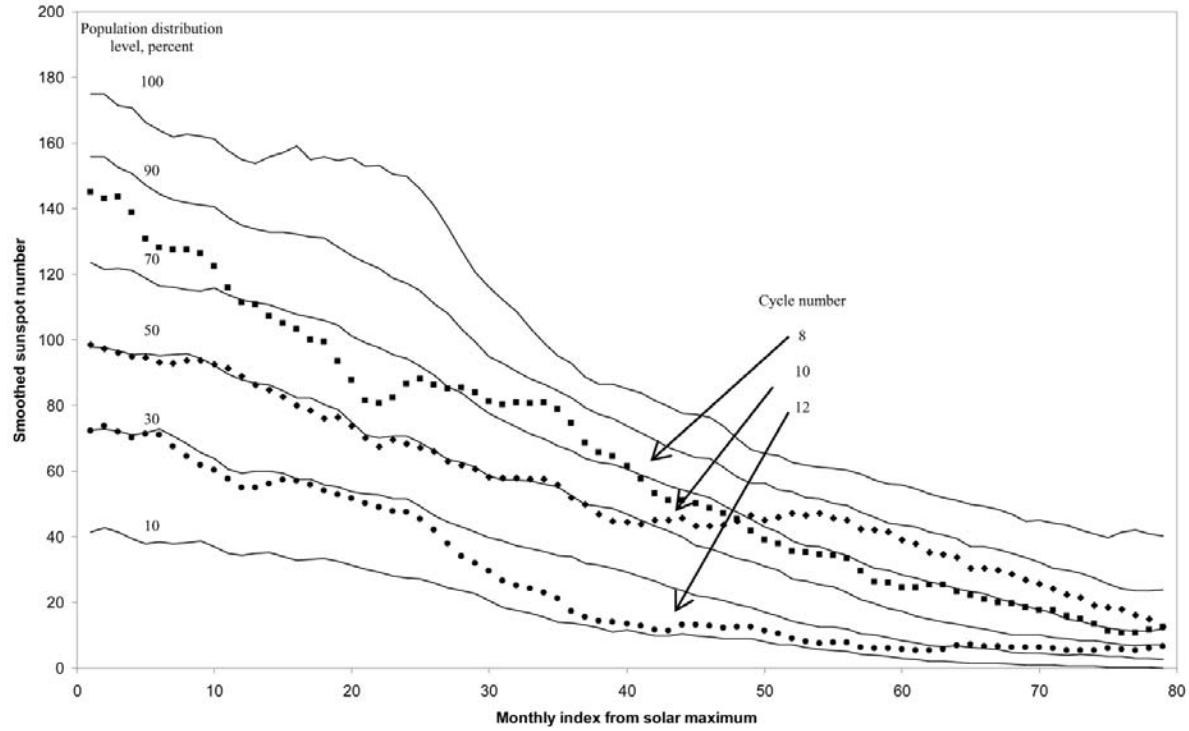


(f) Cycle 23

Figure 4. Concluded.

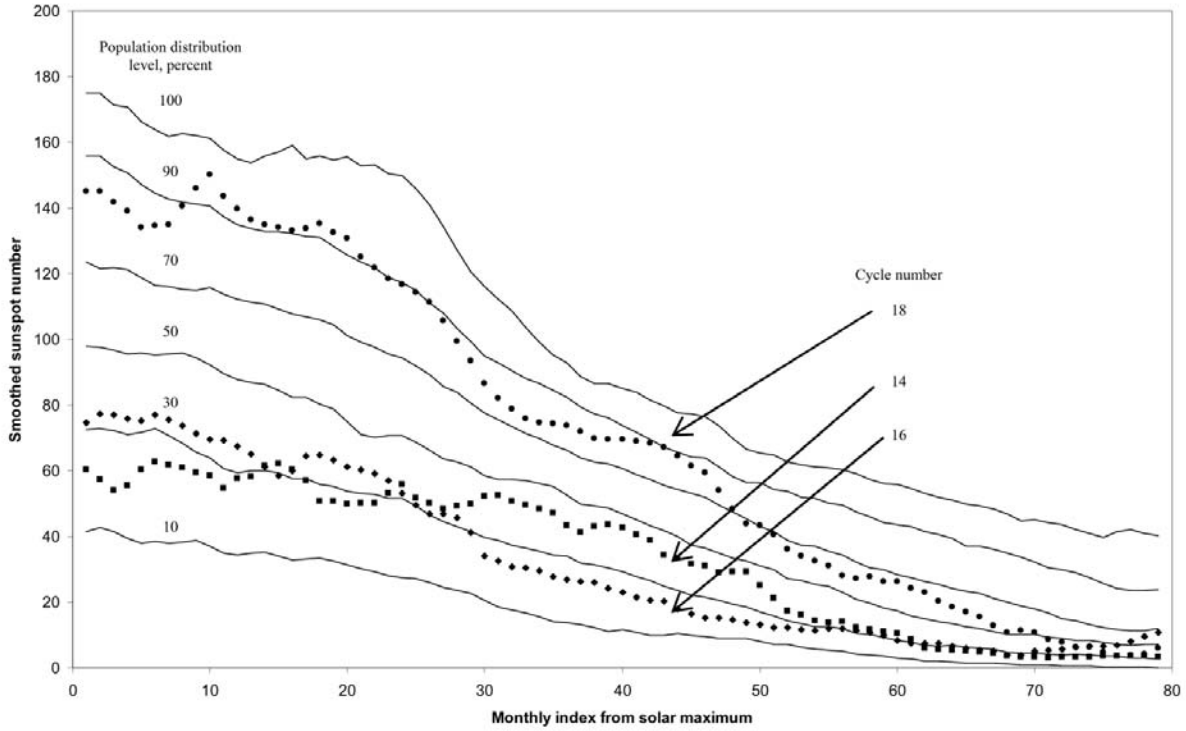


(a) Cycles 2, 4, and 6

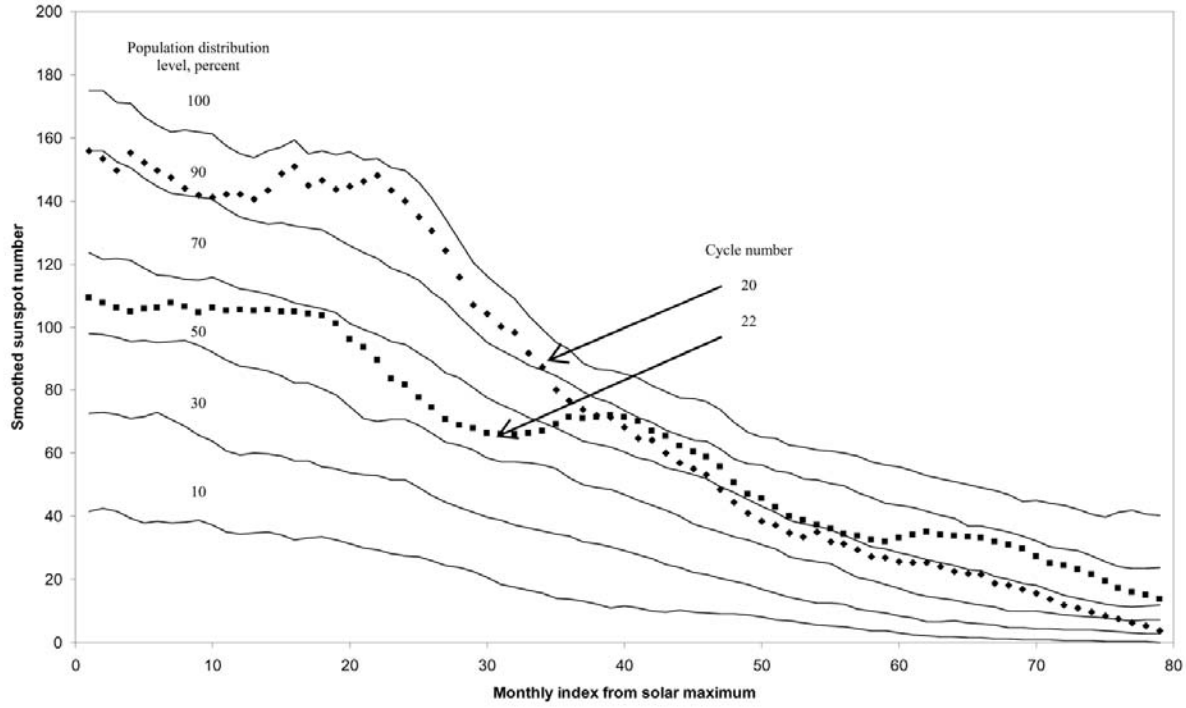


(b) Cycles 8, 10, and 12

Figure 5. Historical sunspot number distribution in declining phase for even cycles.

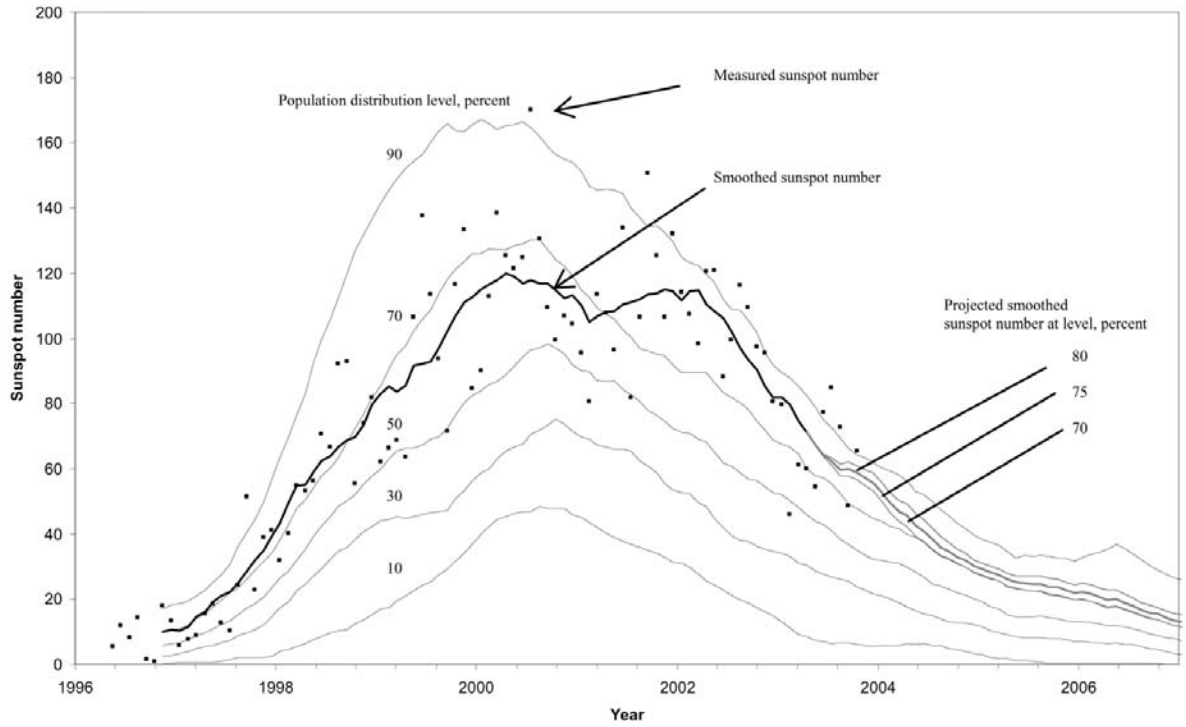


(c) Cycles 14, 16, and 18

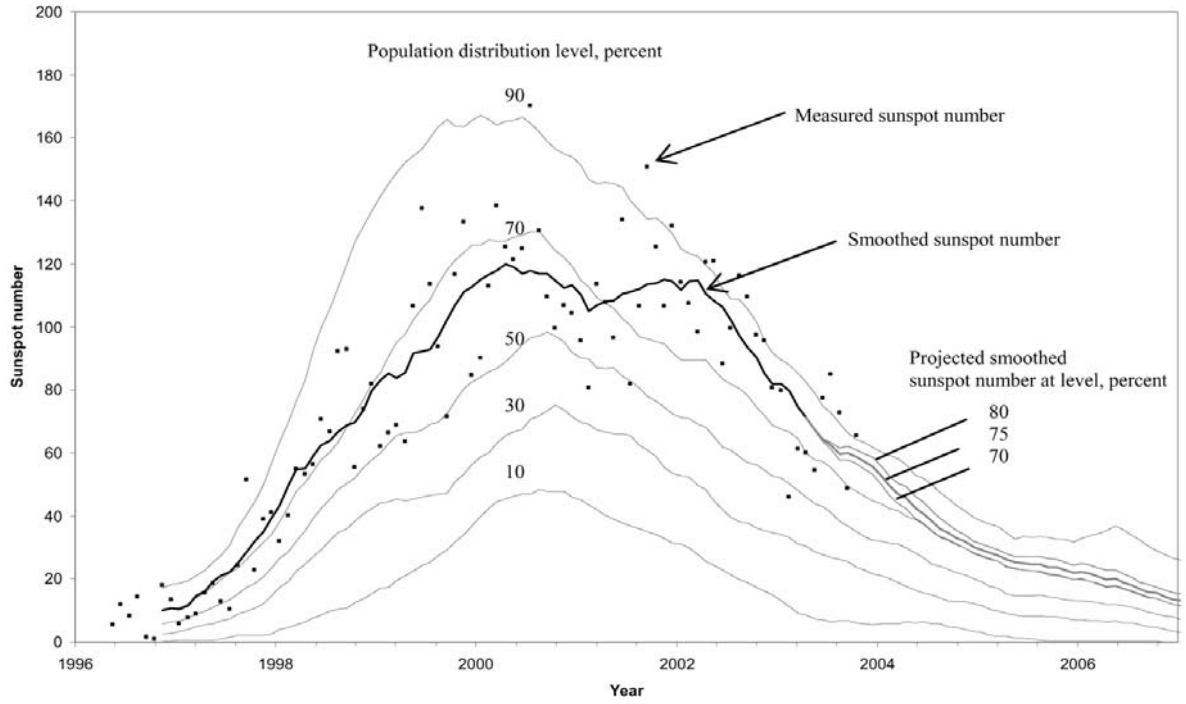


(d) Cycles 20 and 22

Figure 5. Concluded.



(a) Continuous projection to the end of cycle 23 without cycle length considered.



(b) Modified projection near the end of cycle 23 by excluding the data that are extended into the next cycle.

Figure 6. Distribution of sample sunspot numbers in rising and declining phases separately and the projections for projected cycle levels in declining phase of cycle 23.

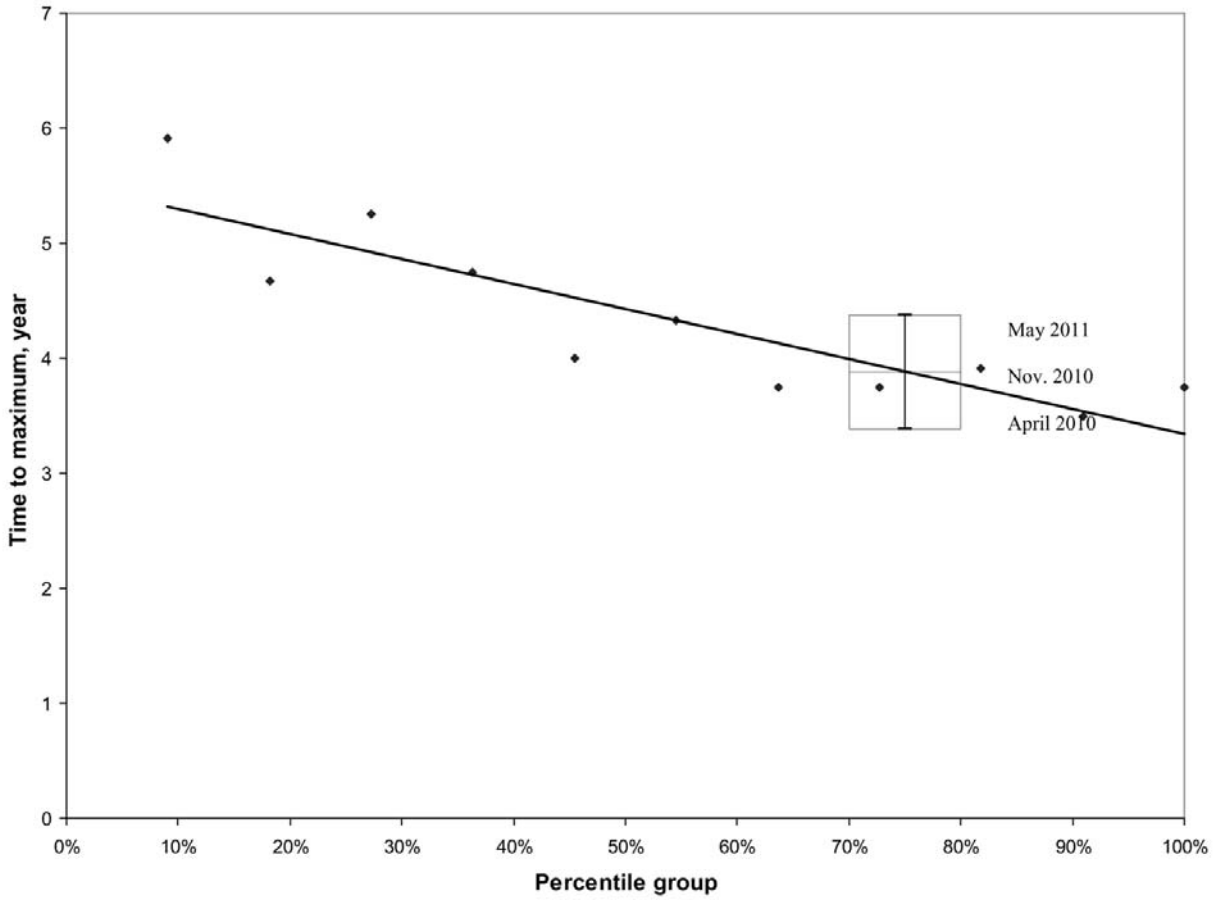


Figure 7. Predicted time to maximum of cycle 24.

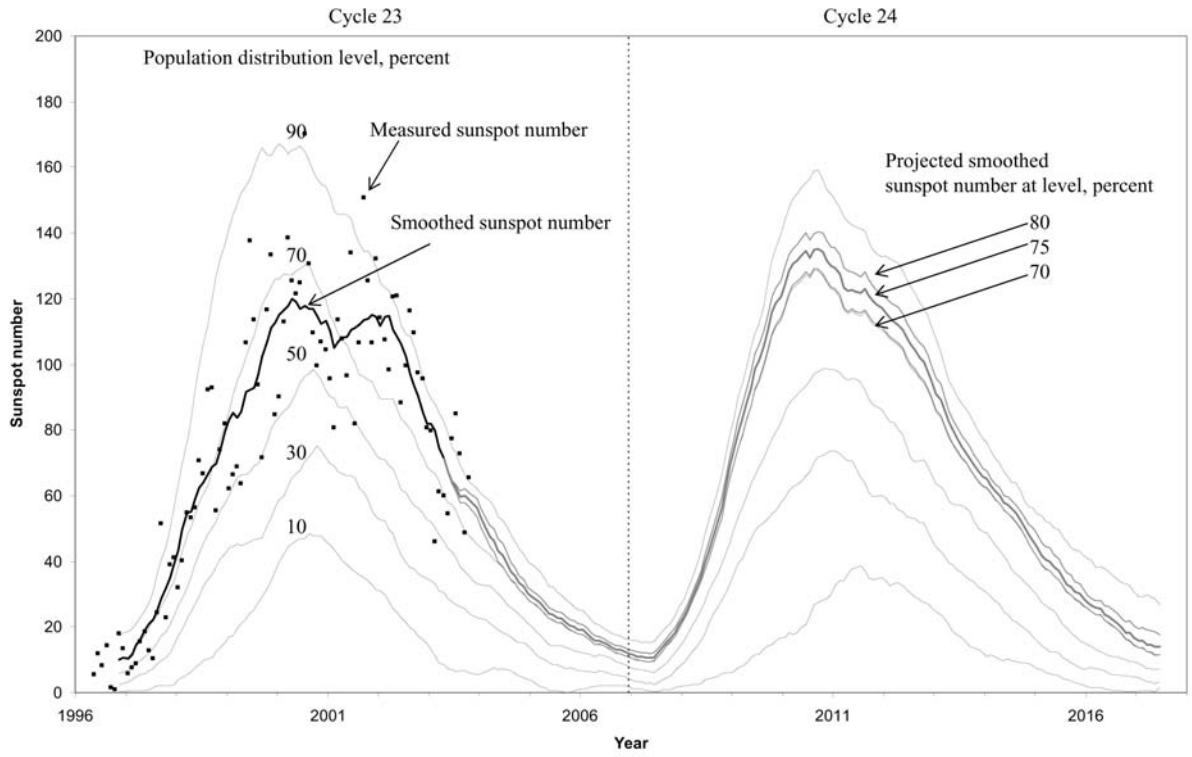


Figure 8. Sampling distribution and projections of cycles 23 and 24.

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13. ABSTRACT *(Maximum 200 words)*

Since the current solar cycle 23 has progressed near the end of the cycle and accurate solar minimum and maximum occurrences have been defined, a statistical model based on the odd-even behavior of historical sunspot cycles was reexamined. Separate calculations of activity levels were made for the rising and declining phases in solar cycle 23, which resulted in improved projection of sunspots in the remainder of cycle 23. Because a fundamental understanding of the transition from cycle to cycle has not been developed, at this time it is assumed for project purposes that solar cycle 24 will continue at the same activity level in the declining phase of cycle 23. Projection errors in solar cycle 24 can be corrected as the cycle progresses and observations become available because this model is shown to be self-correcting.

14. SUBJECT TERMS	15. NUMBER OF PAGES	16. PRICE CODE
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17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
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