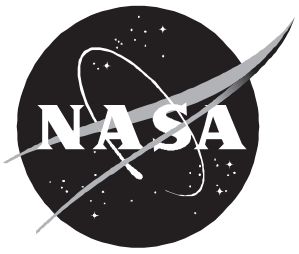
NASA / TP-2000-210536



Examination of Solar Cycle Statistical Model and New Prediction of Solar Cycle 23

Myung-Hee Y. Kim
College of William and Mary, Williamsburg, Virginia

John W. Wilson
Langley Research Center, Hampton, Virginia

October 2000

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at *http://www.sti.nasa.gov*

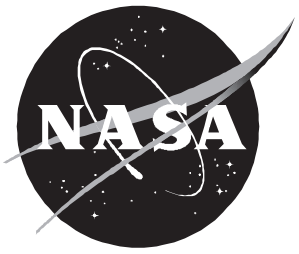
- Email your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Telephone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076-1320

NASA / TP-2000-210536



Examination of Solar Cycle Statistical Model and New Prediction of Solar Cycle 23

Myung-Hee Y. Kim
College of William and Mary, Williamsburg, Virginia

John W. Wilson
Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

October 2000

Available from:

NASA Center for AeroSpace Information (CASI)
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 605-6000

Abstract

Sunspot numbers in the current solar cycle 23 were estimated by using a statistical model with the accumulating cycle sunspot data based on the odd-even behavior of historical sunspot cycles from 1 to 22. Since cycle 23 has progressed and the accurate solar minimum occurrence has been defined, the statistical model is validated by comparing the previous prediction with the new measured sunspot number; the improved sunspot projection in short range of future time is made accordingly. The current cycle is expected to have a moderate level of activity. Errors of this model are shown to be self-correcting as cycle observations become available.

Introduction

A statistical model based on the accumulating cycle sunspot data has been developed to estimate future levels of solar cycle activity, and the sunspot number estimates have been coupled to space-related quantities of interest to radiation protection because the sunspot cycle affects the near-Earth environment (ref. 1). In the previous prediction based on the first 9 months of cycle 23 with an assumed minimum in September 1996, the sequence of cycle 23 was at the level of 82 percent ± 18 percent with a 95-percent confidence interval (ref. 1). Since the cycle has progressed, the beginning of cycle 23 is accurately adjusted as May 1996, which was uncertain when the previous estimation was made; there are 47 observed monthly mean values of sunspot numbers after May 1996 (ref. 2). In the present report, the solar cycle statistical model is evaluated by comparing the measured data with the previous prediction, which shows the new data to be within the confidence interval of the previous analysis but with somewhat lower sunspot numbers. A critical parameter in cycle prediction is seen as the date of solar minimum occurrence. A new mean cycle level of the entire cycle 23 with an adjusted May 1996 start date is made based on the sunspot data for 47 months. New sunspot cycle parameters to the end of cycle 23 are also predicted with the smaller statistical fluctuations. This prediction may be misleading since a randomization process occurs near the cycle end.

Previous Sunspot Number Projection of Cycle 23 With Sunspot Data for 9 Months

The historical sunspot number distributions for 11 separate odd-even cycles are shown in figure 1 for odd cycles and in figure 2 for even cycles along with the associated population distributions of 10, 30, 50, 70, 90, and 100 percent levels as each cycle progresses from its solar minimum. Note that consistent observations are available following the reforms of Wolf during cycle 9 (ref. 3) and prior observations are increasingly uncertain. From the statistically independent patterns of odd-even cycles as seen in figures 1 and 2, a statistical model for solar cycle projection was made for two independent odd-even populations (ref. 1).

By using the previously developed model, the projection of cycle 23 was made based on the assumed minimum in September 1996 and the first 9 months of measured sunspot data (ref. 1). New cycle 23 sunspot data are added to the old projection in figure 3. The current cycle appears to be running its course in the low side of the uncertainty band, which is within the range of the predicted groups, between the 64-percentile and the 82-percentile groups. This comparison validates the previous projection that used only 9 months of data. Since cycle 23 has progressed with a well-defined solar minimum, the percentile group of the expanding cycle 23 observations is reestimated, and better future values within the remainder of the cycle can be defined for the monthly average sunspot numbers.

Solar Minimum for Cycle 23 and Population Distributions for All Odd Cycles

The lowest smoothed sunspot number index for solar cycle 23 occurred in May 1996 (ref. 2). In the previous prediction, the lowest sunspot number index was assumed to occur in September 1996, but it could not be determined precisely until well into cycle 23. From the solar cycle statistical model based on the

odd-even behavior of the solar cycles (ref. 1), the appropriate percentile grouping of cycle 23 can be improved by the correct adjustment of solar minimum for cycle 23 since there is no correlation between odd-even cycles (refs. 4 and 5).

Given the time of solar minimum in the current cycle 23, an appropriate population distribution of sunspot numbers for all odd cycles and the associated cumulative frequency spectrum are regenerated for each successive month to calculate the percentile groups for each month after the cycle 23 minimum, and those distributions are displayed through 2010 in figure 4. Data from the first 47 months of cycle 23 are also shown in figure 4, as solid circles, and in expanded view in figure 5. This figure shows that the sunspot cycle will develop between the 50- and 70-percentile groups of sunspot numbers of previous odd cycles, whereas it ran above the 70-percentile group from the previous prediction in figure 3. This new estimation results from the dependence on the adjustment of solar minimum as well as from more measured data.

Sampling Distributions and New Projection of Cycle 23

The cumulative mean percentile level and statistical fluctuation of the sample sunspot numbers at each month in the current cycle are calculated for the range of percentile groups. This calculation is illustrated in figure 6. At the beginning of the present solar cycle 23, the monthly sunspot number in May 1996 is on the 91-percentile level of sunspot numbers of previous odd cycles. As cycle observations become available, it is clearly shown that the uncertainty in mean percentile grouping is contracting about expanding current data. The mean percentile grouping of the current cycle is 66 percentile, with a standard deviation of 17 percent using the data for the first 47 months that are up to March 2000. From these sample distributions of size 47 of a normal population of the current cycle 23, the mean cycle level of the entire cycle 23 would be at 66 percent ± 5 percent with 46 degrees of freedom and with a 95-percent confidence interval.

Long-term projections based on the results of figure 6 are shown in figure 7. In figure 7, the 13-month running average sunspot number and monthly values of the observations are also shown. Projections over more than one cycle are difficult because they introduce uncertainties not only in the future amplitude, due to randomization near the cycle boundary, but also reflect uncertainty in the cycle duration (ref. 6). Hence, the estimate of the next solar maximum and minimum is uncertain, in addition to the corresponding sunspot numbers.

Predictions of Solar Maximum for Cycle 23 and Duration of Cycle 23

Using the current progressive trend, the new estimate of the time to the next solar maximum is shown in figure 8. Hence, the next solar maximum is currently projected to be in August 2000, with an uncertainty of 10 months. The duration of cycle 23 is similarly analyzed in figure 9, and the next solar minimum is expected to be in January 2007, with an uncertainty of 13 months. These two figures clearly show that errors are self-correcting as cycle observations become available. The corresponding annual averaged maximum sunspot number is expected to be 117, with an uncertainty of 7. The sunspot minimum in January 2007 is expected to be 13, with an uncertainty of 1. The estimates of cycle 23 maximum and cycle 24 minimum values are given in table 1. The mean cycle level of the entire cycle 23 would be at 66 percent ± 5 percent with 46 degrees of freedom and with a 95-percent confidence interval as shown in figure 10 along with historical sunspot levels of all odd cycles.

Table 1. Statistical Prediction of Sunspot Cycle Parameters

Parameter	Low end of range		Average		High end of range	
	Date	Sunspot number	Date	Sunspot number	Date	Sunspot number
Smoothed cycle 23 maximum	June 2001	111	August 2000	117	October 1999	124
Smoothed cycle 24 minimum	February 2008	12	January 2007	13	December 2005	14

Concluding Remarks

A previously developed statistical model, which is based on only the first 9 months of data, has been examined in predicting the solar cycle variation. As the cycle progresses with 47 available observable, a convergence toward improved estimates is achieved. From the sample of size 47 of the current cycle, the mean cycle level of the entire cycle 23 would be at 66 percent ± 5 percent with 46 degrees of freedom and with a 95-percent confidence interval. Even though there is still a problem in cycle projection from one cycle to the next due to a randomization process at the end of each cycle, solar maximum of cycle 23 and the duration of the current cycle are predicted with a much smaller fluctuation than the previous one. The corresponding annual averaged maximum sunspot number and the next minimum sunspot number are also predicted. The current projection will provide a basis of estimating exposures in future missions. The effect of uncertainties of solar cycle predictions on future shield design requires further study. Only a dynamic model based on some yet unidentified observable factor will allow reliable predictions of successive cycle dependence.

References

1. Wilson, John W.; Kim, Myung-Hee Y.; Shinn, Judy L.; Tai, Hsiang; Cucinotta, Francis A.; Badhwar, Gautam D.; Badavi, Francis F.; and Atwell, William: *Solar Cycle Variation and Application to the Space Radiation Environment*. NASA/TP-1999-209369, 1999.

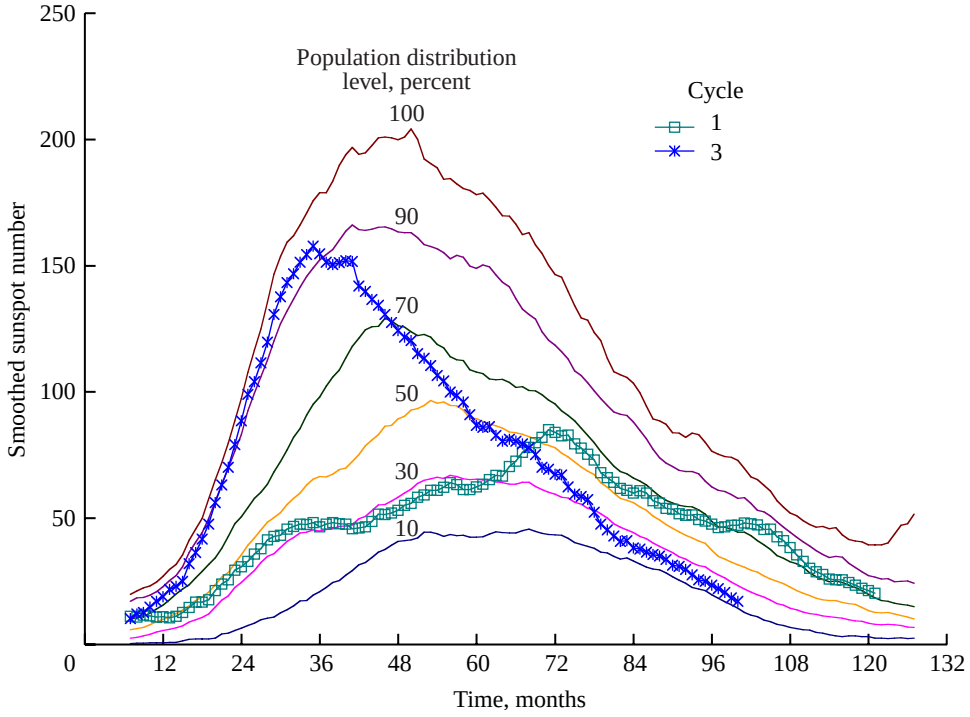
2. Space Environment Center: Preliminary Report and Forecast of Solar Geophysical Data—The Weekly. NOAA, http://www.sec.noaa.gov/weekly.html Accessed Aug. 15, 2000.

3. Eddy, John A.: The Maunder Minimum. *Science*, vol. 192, no. 4245, June 1976, pp. 1189–1202.

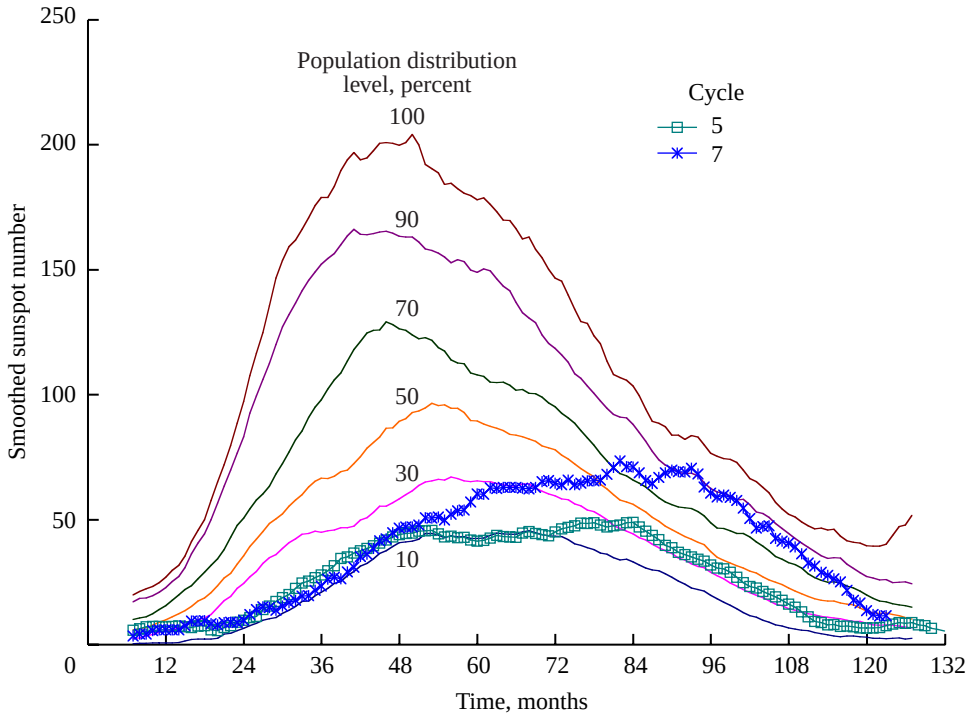
4. Hale, G. E.: Magnetic Field in Sun-Spots. *Astrophys. J.*, vol. 28, 1908, pp. 315–343.

5. Babcock, H. W.: The Topology of the Sun's Magnetic Field and the 22-Year Cycle. *Astrophys. J.*, vol. 133, no. 2, Mar. 1961, pp. 572–587.

6. Withbroe, George L.: Solar Activity Cycle: History and Predictions. *J. Spacecr. & Rockets*, vol. 26, no. 6, Nov.–Dec. 1989, pp. 394–402.

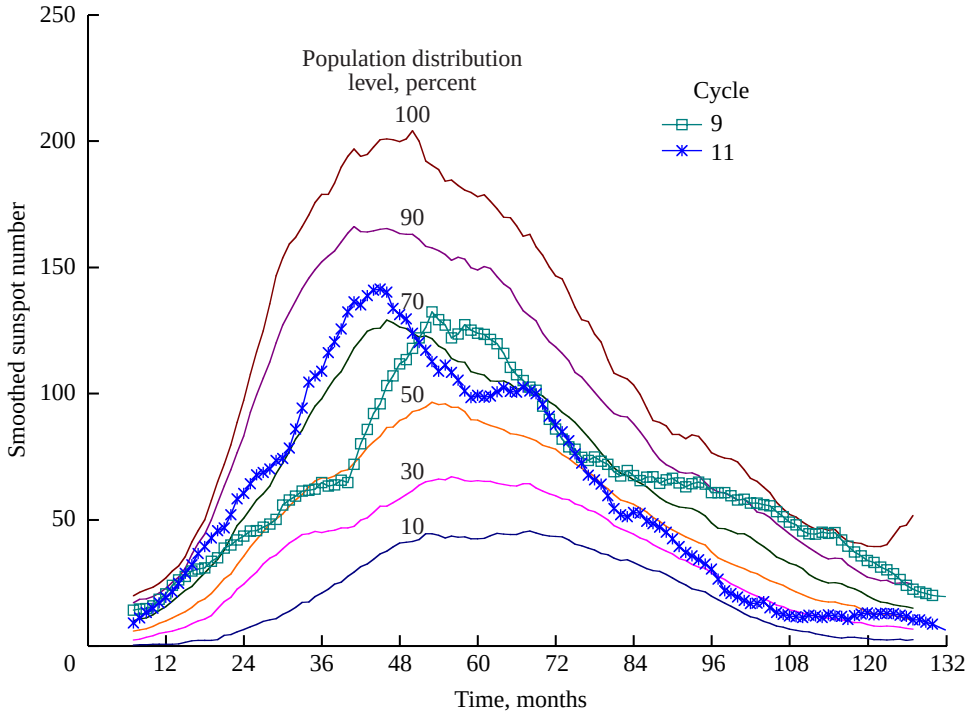


(a) Cycles 1 and 3.

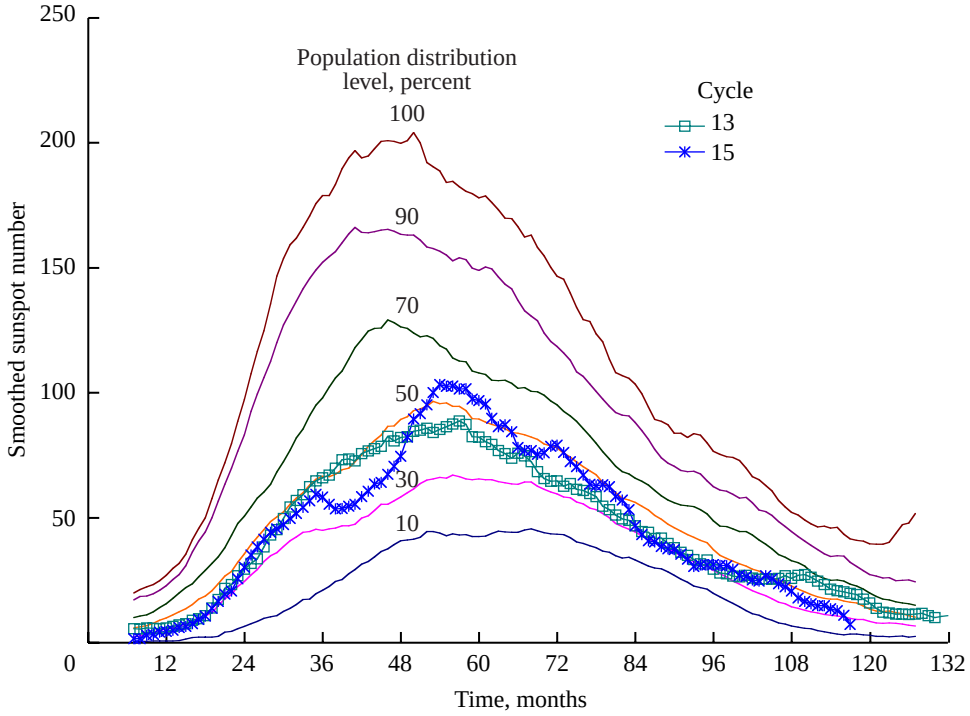


(b) Cycles 5 and 7.

Figure 1. Historical sunspot number distribution for odd cycles.

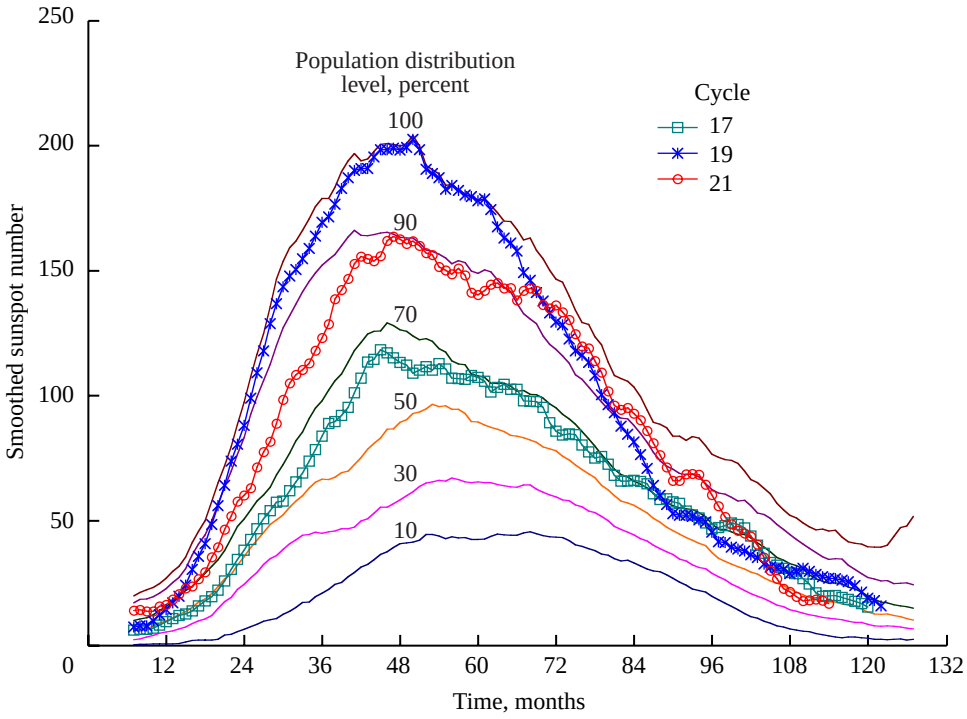


(c) Cycles 9 and 11.



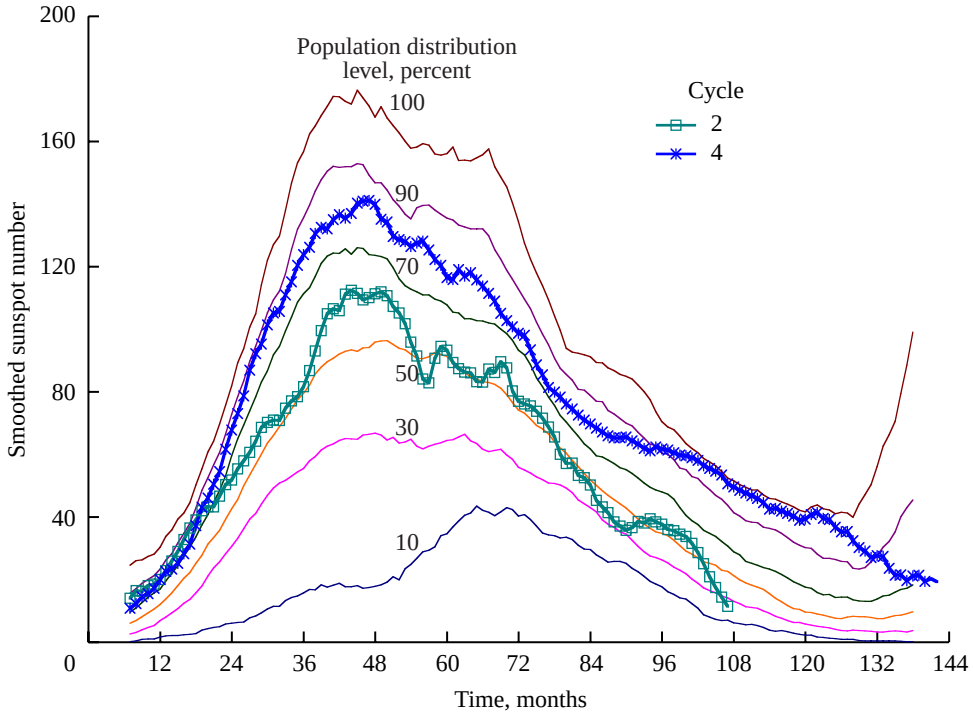
(d) Cycles 13 and 15.

Figure 1. Continued.

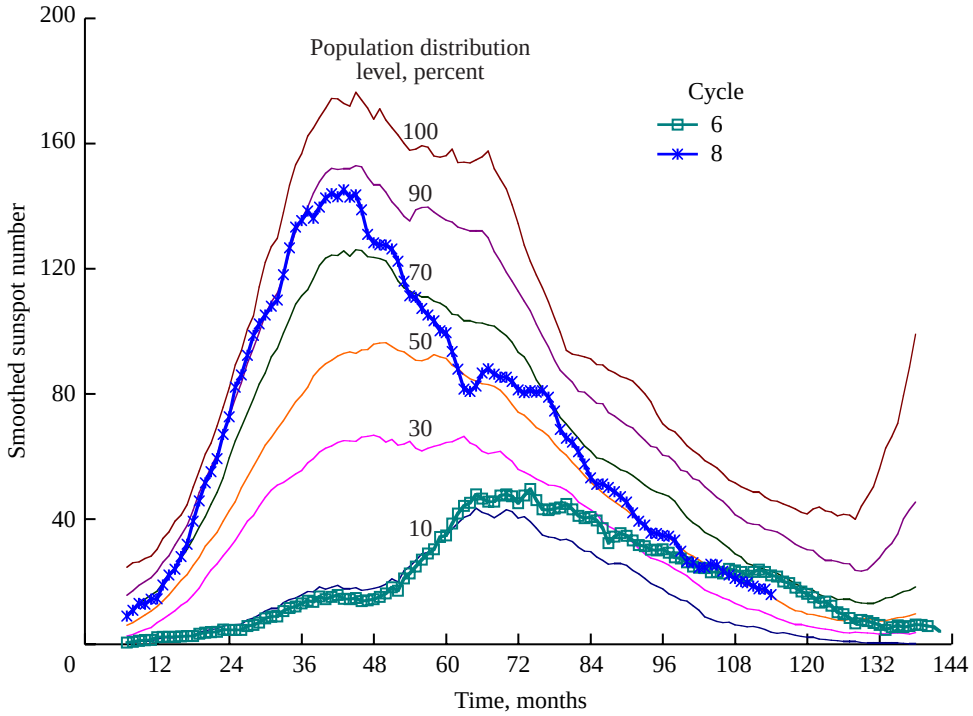


(e) Cycles 17, 19, and 21.

Figure 1. Concluded.

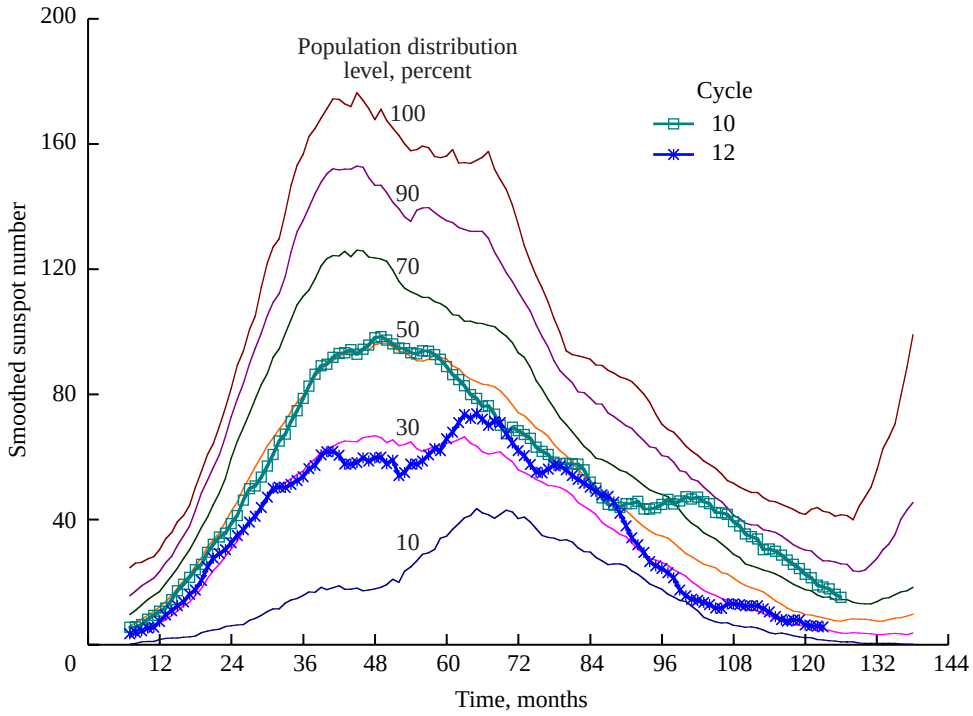


(a) Cycles 2 and 4.

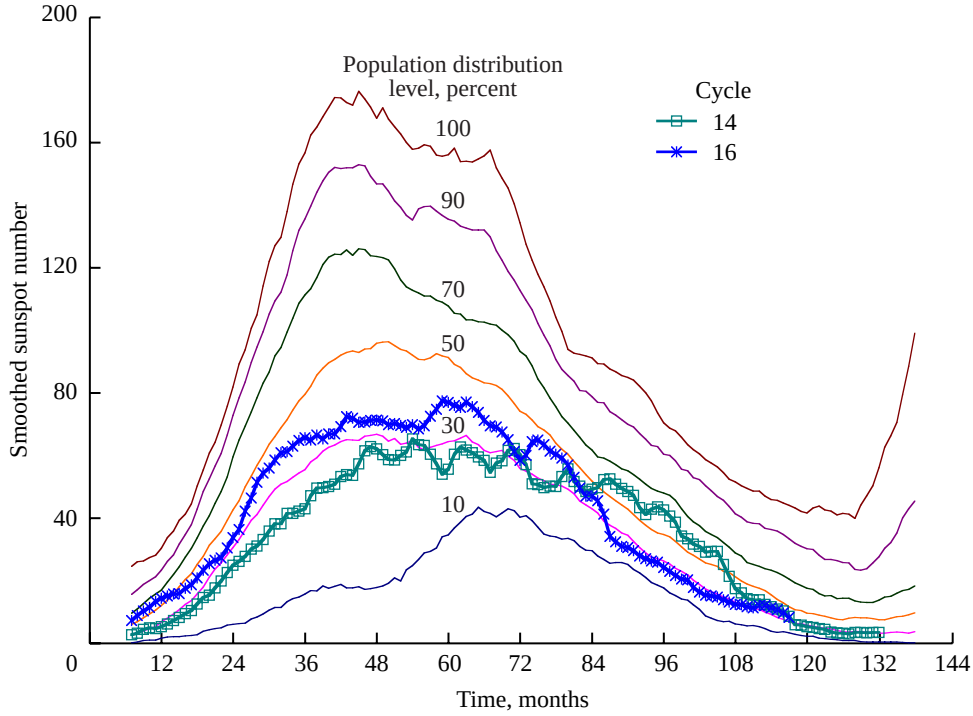


(b) Cycles 6 and 8.

Figure 2. Historical sunspot number distribution for even cycles.

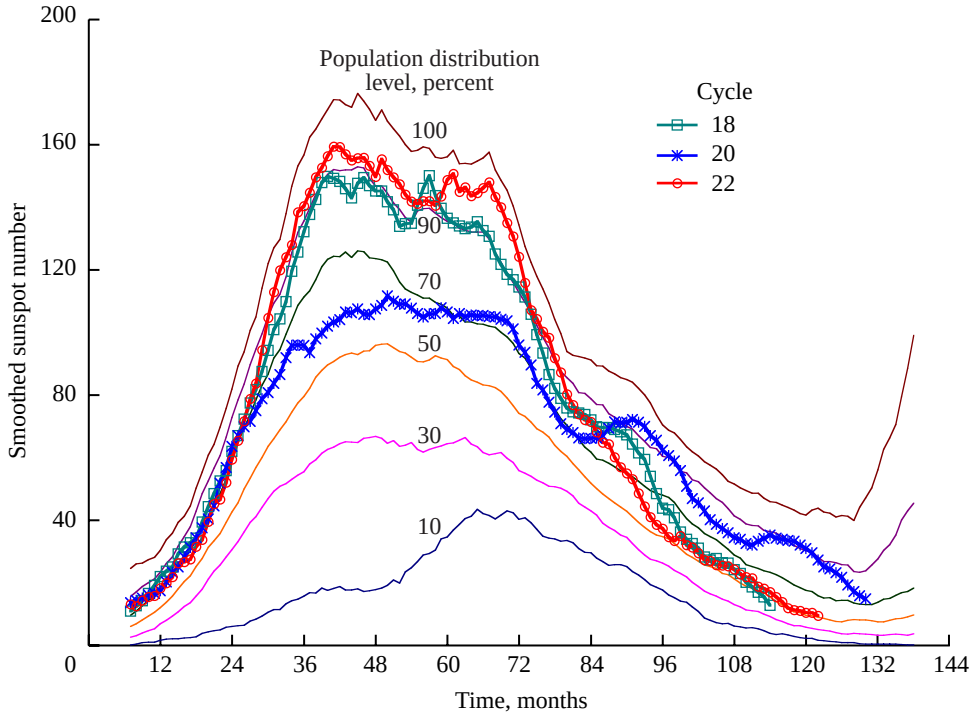


(c) Cycles 10 and 12.



(d) Cycles 14 and 16.

Figure 2. Continued.



(e) Cycles 18, 20, and 22.

Figure 2. Concluded.

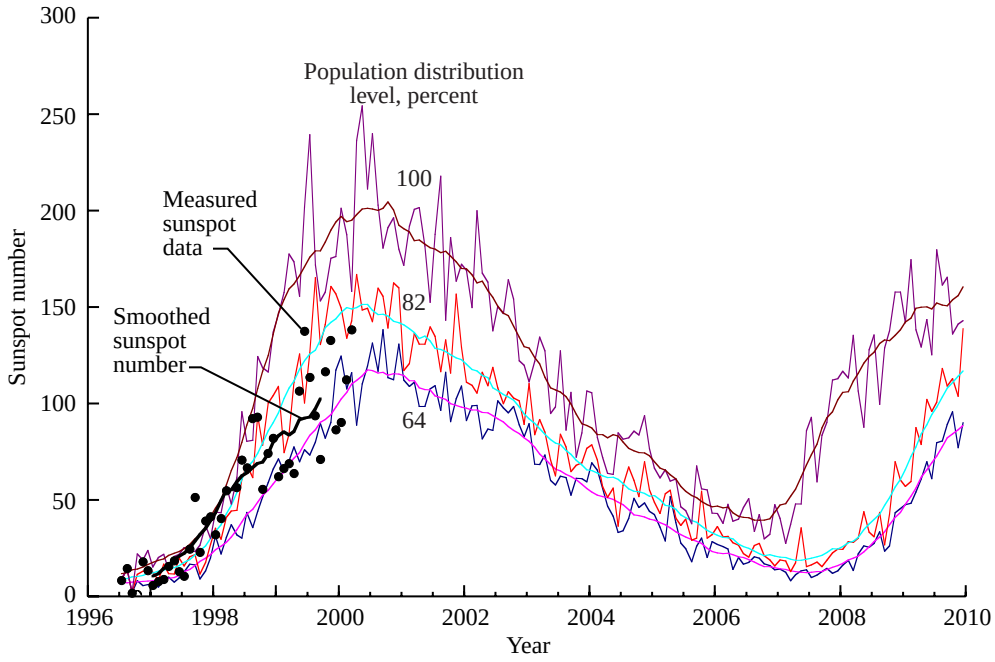


Figure 3. Previous projection of cycle 23 sunspot number and statistical uncertainty with new cycle 23 sunspot data added since projection was made.

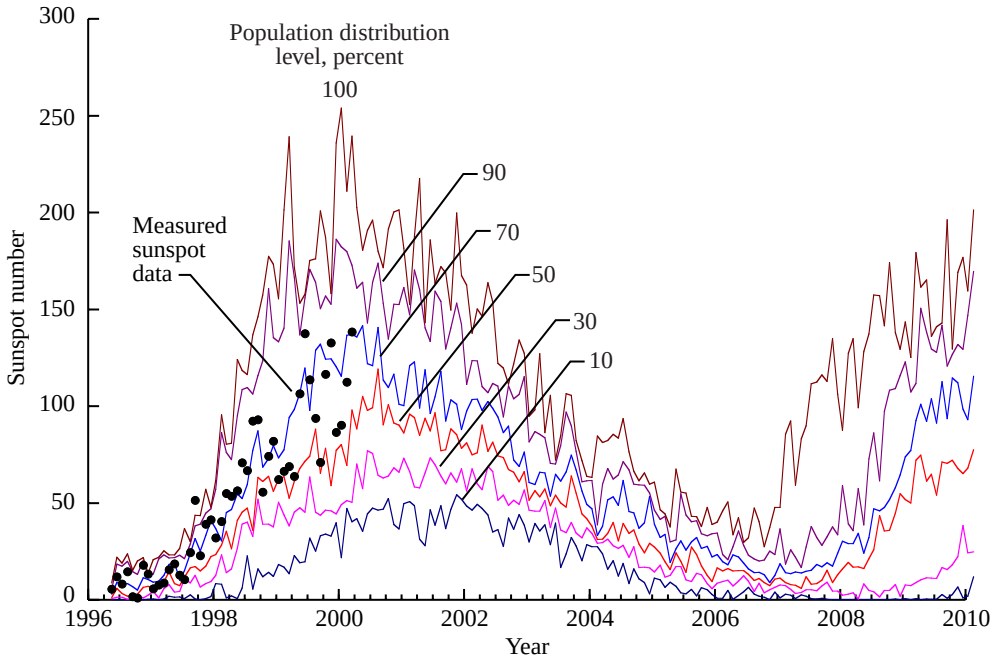


Figure 4. New projection of cycle 23 sunspot number and statistical uncertainty with measured sunspot data.

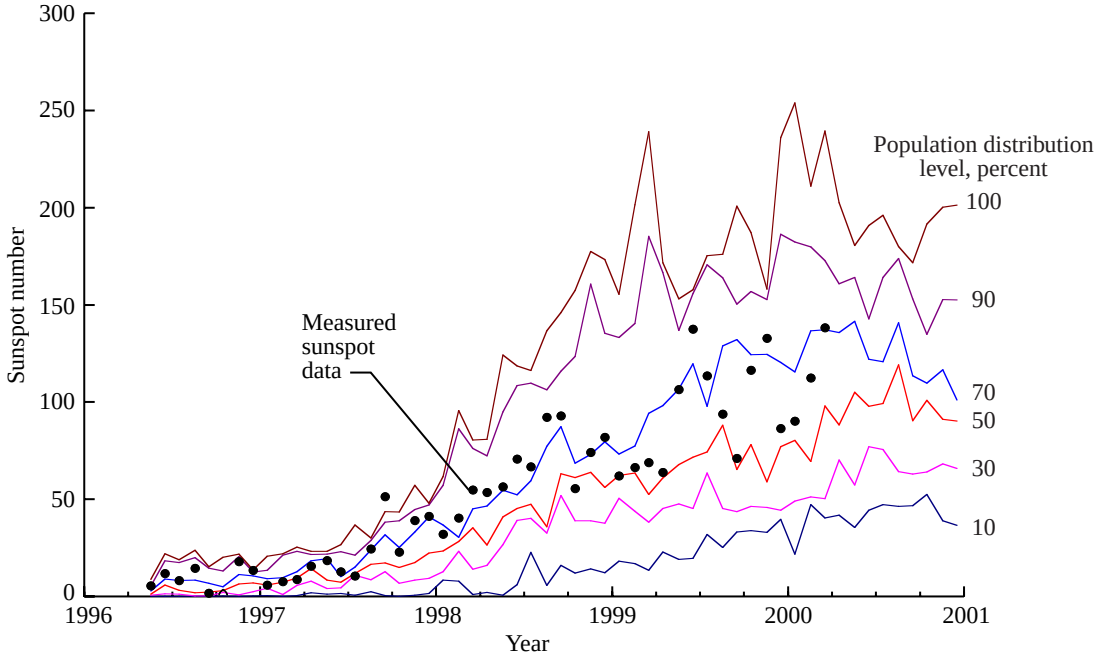


Figure 5. First 47 months of cycle 23 used to determine population group of cycle 23.

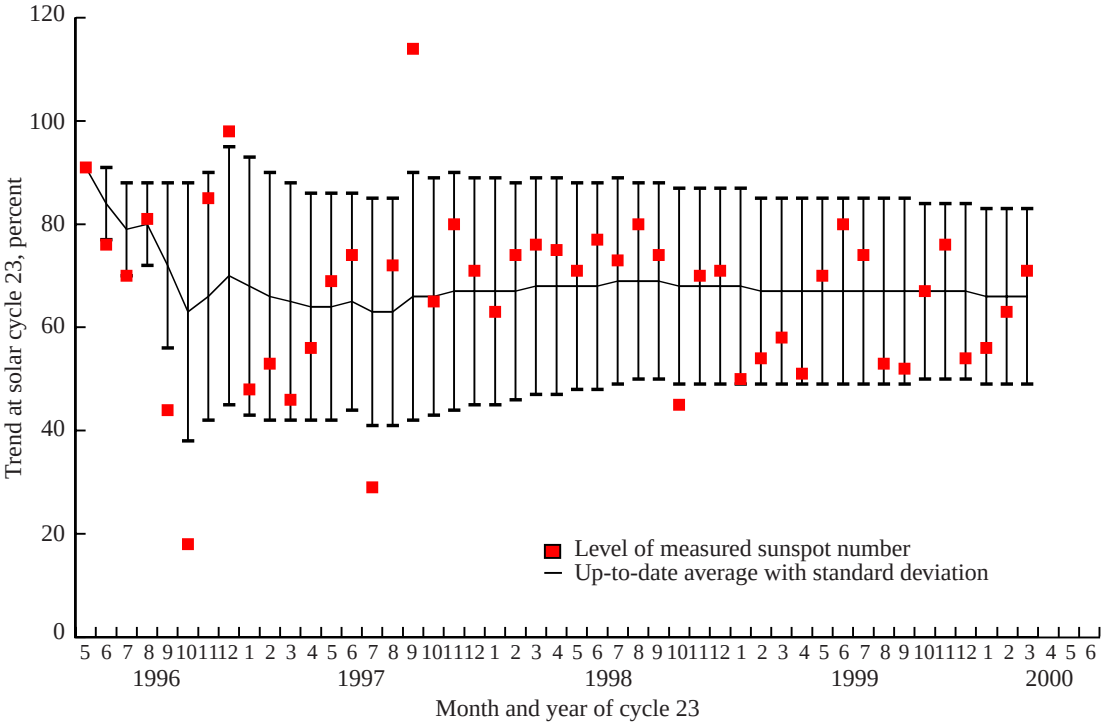


Figure 6. Percentile group of first 47 months of cycle 23 and cumulative mean value and statistical fluctuation.

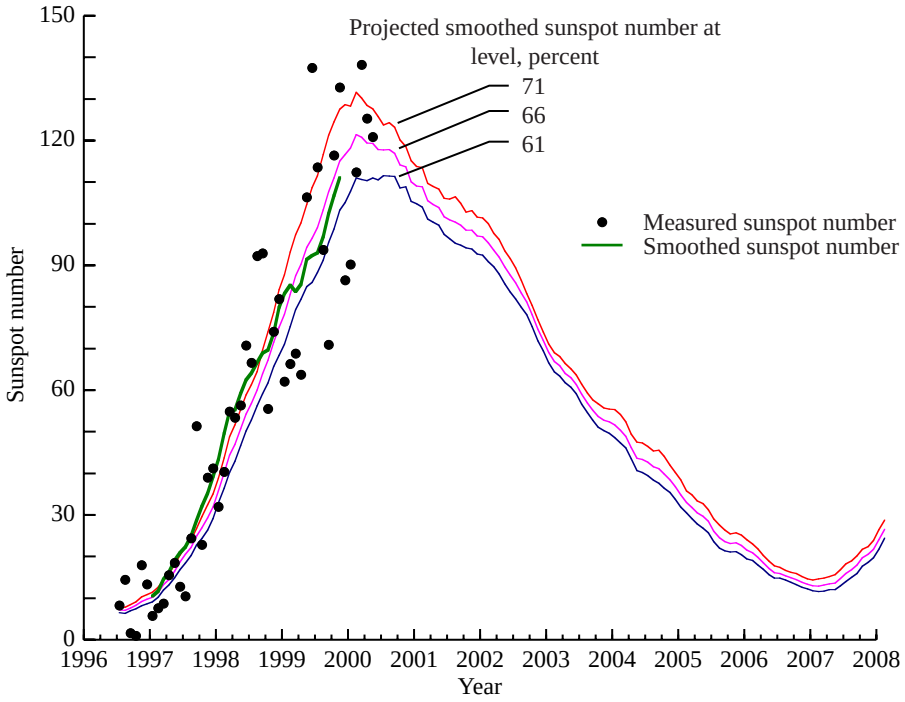


Figure 7. Distribution of sample sunspot numbers and long-term projections for projected cycle levels of cycle 23.

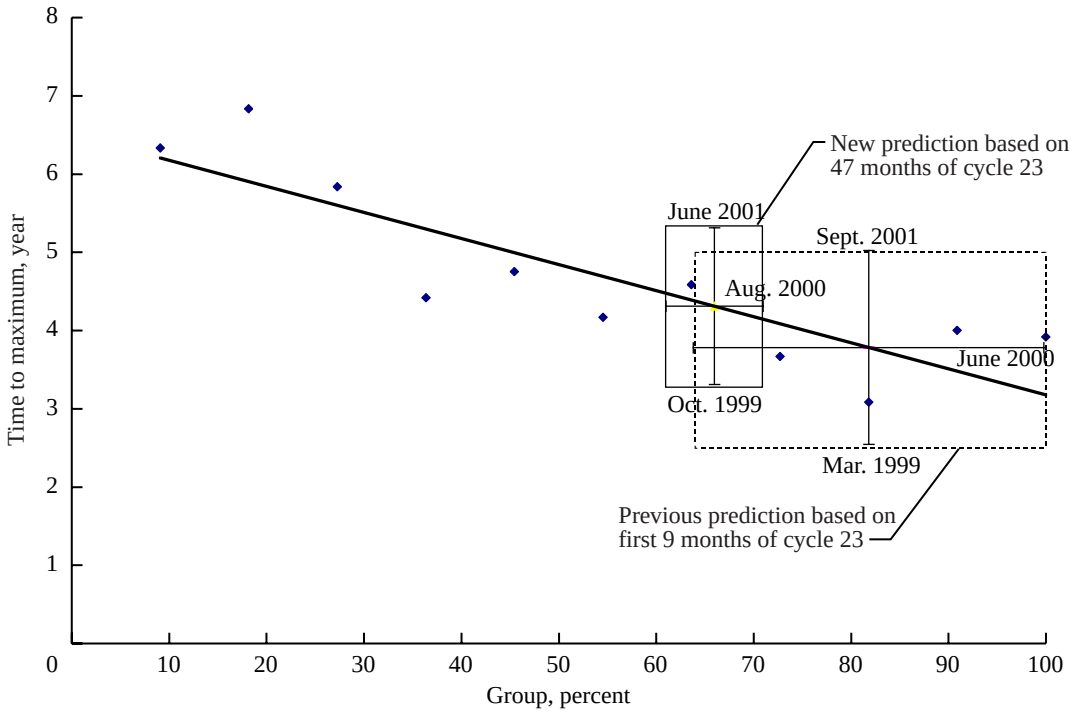


Figure 8. Predicted time to maximum of cycle 23.

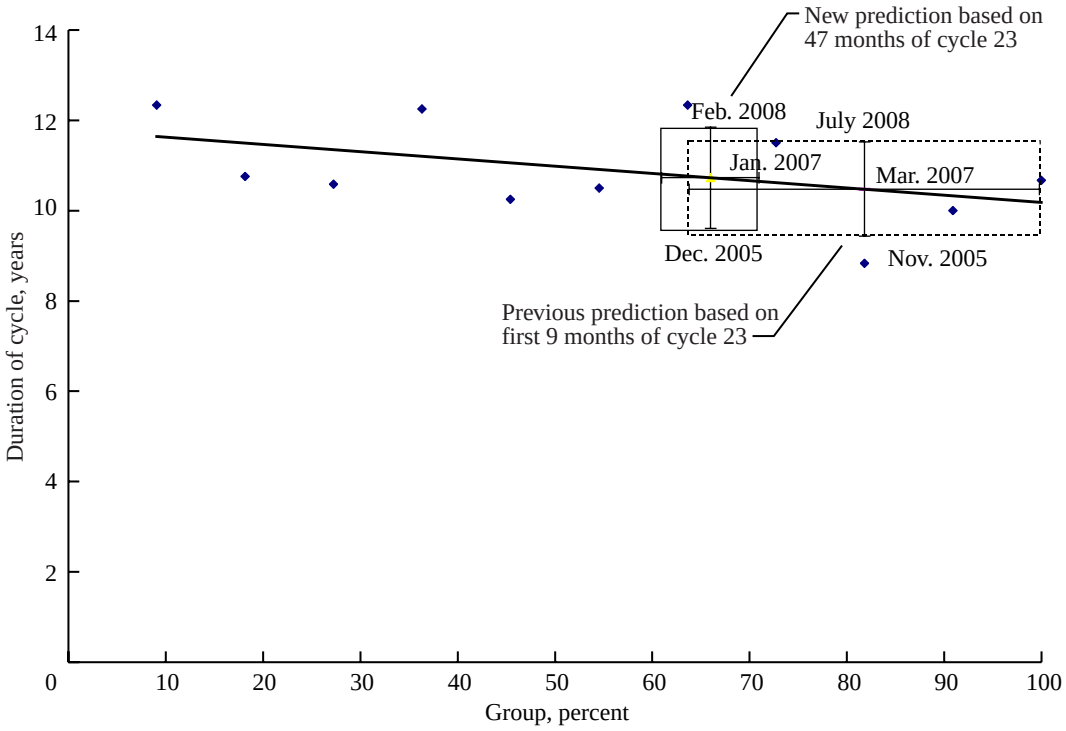


Figure 9. Predicted duration of cycle 23.

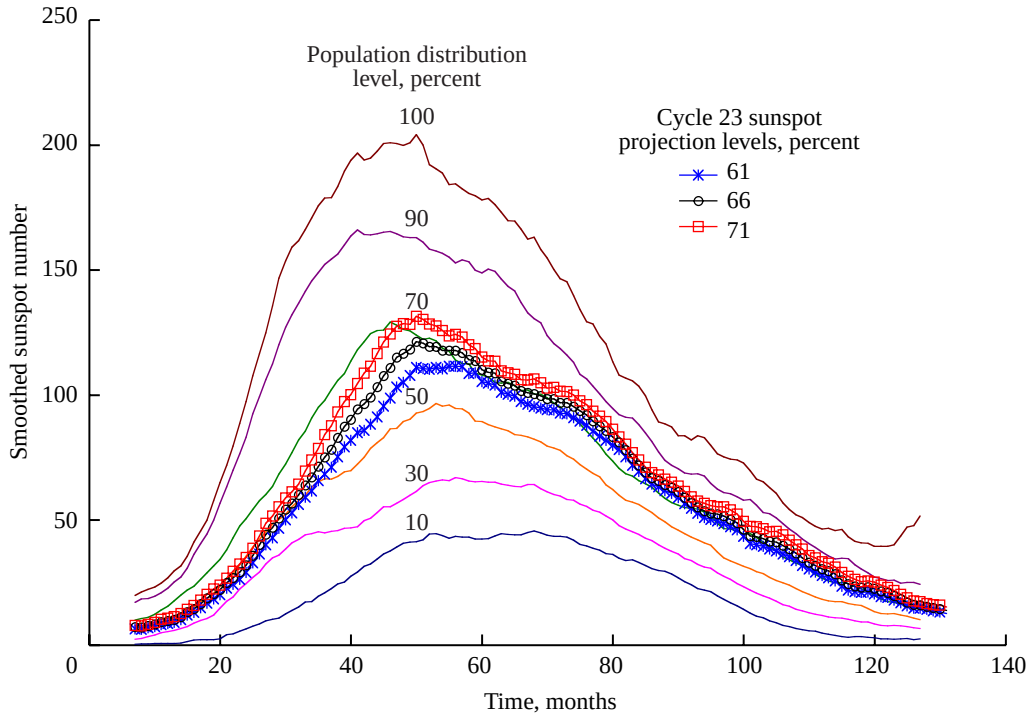


Figure 10. Predicted cycle 23 of all odd cycles.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 2000	Technical Publication

4. TITLE AND SUBTITLE
Examination of Solar Cycle Statistical Model and New Prediction of Solar Cycle 23

5. FUNDING NUMBERS
WU 632-84-01-01

6. AUTHOR(S)
Myung-Hee Y. Kim and John W. Wilson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-18020

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TP-2000-210536

11. SUPPLEMENTARY NOTES
Kim: College of William and Mary, Williamsburg, VA; Wilson: Langley Research Center, Hampton, VA.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified–Unlimited
Subject Category 93 Distribution: Standard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Sunspot numbers in the current solar cycle 23 were estimated by using a statistical model with the accumulating cycle sunspot data based on the odd-even behavior of historical sunspot cycles from 1 to 22. Since cycle 23 has progressed and the accurate solar minimum occurrence has been defined, the statistical model is validated by comparing the previous prediction with the new measured sunspot number; the improved sunspot projection in short range of future time is made accordingly. The current cycle is expected to have a moderate level of activity. Errors of this model are shown to be self-correcting as cycle observations become available.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Solar cycles; Statistical model; Sunspot number prediction	18
	16. PRICE CODE: A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL