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Solar Cycle 23 Project: Summary of Panel Findings

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Introduction

The objective of the Solar Cycle 23 Project is to survey forecasts for the amplitude and phasing of the most common indicators of solar and geomagnetic activity (Sunspot Number, 10.7 cm solar flux, *aa*, A_p) for Solar Cycle 23 and to recommend a forecast or group of forecasts for operational use. To reach this objective, the NOAA Space Environment Center (SEC), with the support of the NASA Office of Space Science, recruited a scientific panel to assess prediction techniques and arrive at a reasoned consensus, including uncertainty, on how the solar cycle will develop. The panel, consisting of 12 scientists from 10 agencies (including representatives from Australia, Germany, the United Kingdom, and the United States) convened September 9 - 25, 1996, in Boulder, Colorado. This report summarizes the findings of the panel, the data and concepts considered, and the process used to arrive at the results. A more detailed report will be available as a NOAA Technical Memorandum, and as an article in the open literature.

Predictions of solar and geomagnetic activity are important to various technologies, including the operation of low-Earth orbiting satellites, electric power transmission grids, geophysical exploration, and high-frequency radio communications and radars. The scale height of Earth's upper atmosphere (and thus the drag on satellites in low Earth orbit) is dependent on the intensity of short-wavelength solar radiation and the level of geomagnetic activity, so knowledge of the profile and magnitude of the next solar and geomagnetic cycle is crucial for logistical planning for reboosting the Hubble Space Telescope and assembly of the International Space Station.

The general trend in recent solar activity cycles (Figure 1) is toward larger amplitude sunspot cycles; Cycle 19 was the largest in recorded history (smoothed sunspot number maximum of 201 in March, 1958), and Cycle 22 was the third largest (smoothed maximum of 159 in July, 1989). Cycles 21 and 22 both showed annual averages of geomagnetic activity that were large in comparison with most cycles in the record of *aa* indices (Figure 2). The dramatic variability from one cycle to the next in these sunspot and geomagnetic records shows the difficulty in making empirical predictions of both types of activity. The issue is further complicated by the lack of a successful quantitative, theoretical model of the Sun's magnetic cycle.

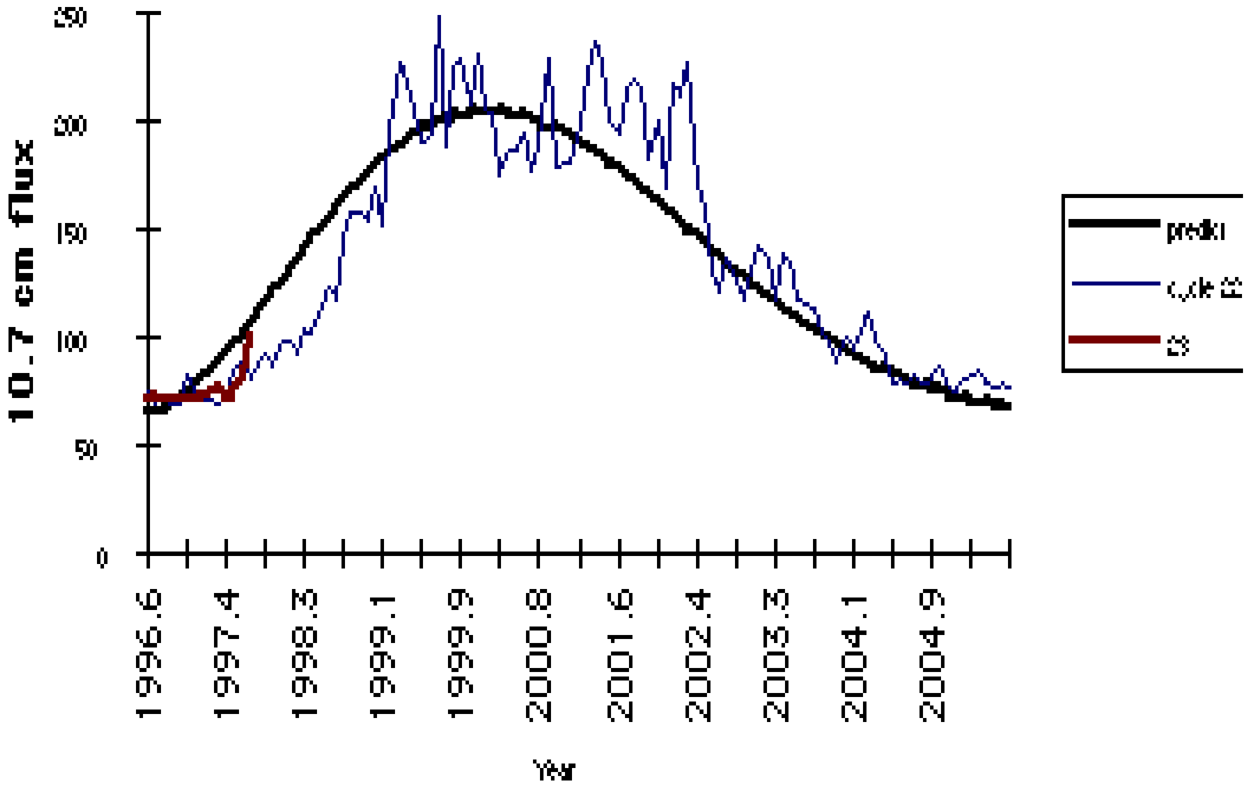

Figure 1. Annual Sunspot Numbers, 1840-1995; cycles are labeled with their associated numbers.

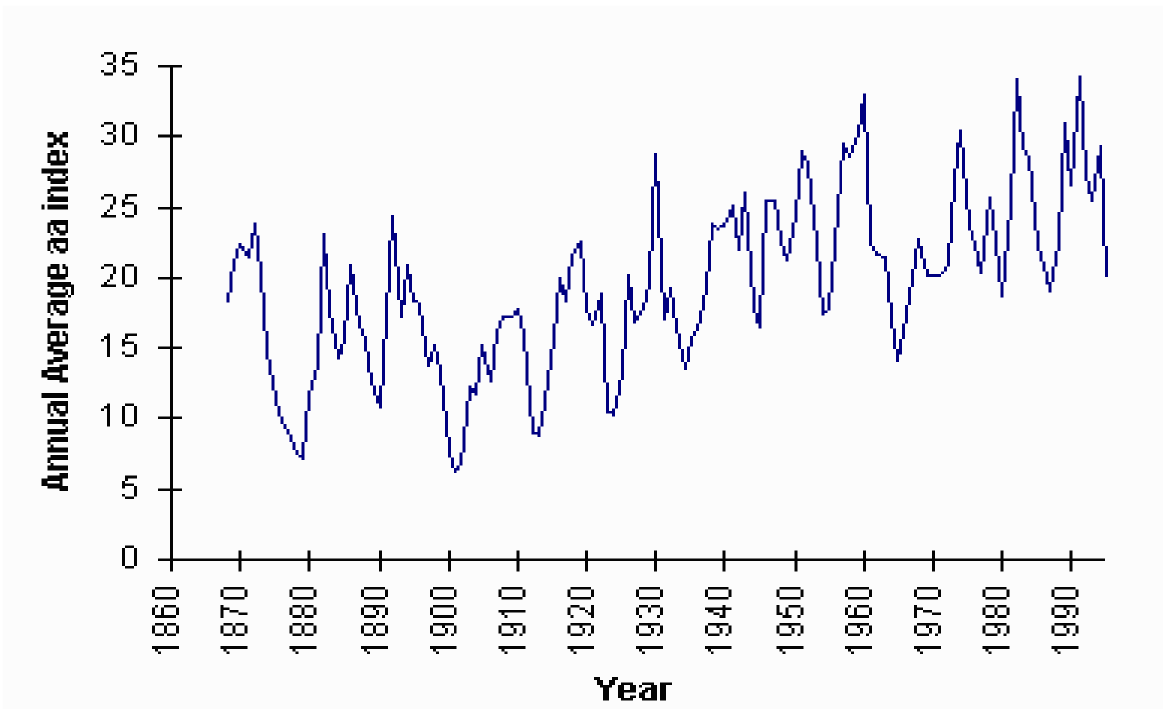

Figure 2. Annual average *aa* geomagnetic index, 1868-1995.

Prediction of the Sunspot Number and 10.7 cm Solar Flux

In advance of the panel meeting, forecasts of solar and geomagnetic activity were requested from the scientific community through the electronic newsletters of the appropriate sections of the American Geophysical Union and the American Astronomical Society; replies were considered by the panel along with forecasts published in the open literature. To place all forecasts on the same footing, 10.7 cm flux values were converted to an equivalent sunspot number. The resulting 28 forecasts were then separated into 6 classes according to the nature of the prediction technique used. The predictions in each class were then considered in detail and a "representative" prediction was selected. These values are given in Table 1 in descending order of the predicted maximum. In the table, "Recent Climatology" considers only Cycles 18 and later, but the mean characteristics of all (or nearly-all) known cycles are considered in "Climatology (all)."

Table 1: Combined forecasts of maximum smoothed sunspot number for classes of prediction techniques

Technique	low end of range	maximum	high end of range
Even/Odd behavior	165	200	235
Precursor	140	160	180
Spectral	135	155	185
Recent Climatology	125	155	185
Neural Networks	110	140	170
Climatology (all)	75	115	155

While four of the six techniques are in general agreement, the panel gave the greatest weight to precursor methods, since they have proved to be the most successful technique for solar activity predictions in the past. These methods utilize the concept of an "extended solar cycle" the idea that the imminent solar cycle actually starts in the declining phase of the previous cycle. In the declining phase and at solar minimum, the coming cycle manifests itself in the occurrence of structures such as coronal holes and the strength of the solar polar magnetic field. High speed solar wind streams from low-latitude coronal holes give rise to recurrent geomagnetic disturbances that are used as the predictor of the strength of the next cycle (e.g., Thompson [1993]). The precursor methods invoke a solar dynamo concept, where the polar field in the declining phase and at minimum is the seed of future toroidal fields within the sun that will cause solar activity (e.g., Schatten and Pesnell [1993]). The dependence on the strength of the solar polar field also offers an explanation of why geomagnetic precursors serve as proxies for predicting the solar cycle physical connection exists between the polar field, coronal holes, the interplanetary field, and geomagnetic activity.

The prediction technique based on the empirical result that odd-numbered cycles are larger than their preceding cycle, suggests that the next cycle will exceed Cycle 22 and could be larger than Cycle 19. The general trend of cycle amplitudes is also increasing; recent cycles have been large (see Figure 1). Based on such an analysis, there is a reasonable probability that Cycle 23 will equal, or exceed, Cycle 19. This does not, however, consider the observed conditions that are the basis of the precursor technique. The conditions presently being observed in the Sun-Earth environment are not consistent with those observed prior to Cycle 19 and do not support the idea that Cycle 23 will be as large as Cycle 19.

The representative predictions in Table 1 were combined to obtain a consensus prediction for the panel. This is listed in Table 2 for sunspot number and for 10.7 cm solar flux. Combining such different techniques was a difficult process and in doing so, the panel made use of its experience and knowledge of the techniques and their success in predicting previous cycles specially Cycles 21 and 22.

Table 2: Consensus prediction

Parameter	low end of range	maximum	high end of range
Smoothed Monthly Sunspot Number	130	160	190
Smoothed Monthly 10.7 cm Solar Flux	175	205	235

The general profile of Cycle 23 depends on factors like the time of minimum, the rise time (minimum to maximum), and the maximum amplitude of the cycle. Based on current information, the smoothed minimum will most likely occur after April 1996 and before March 1997, most likely in late 1996.

In advance of a confirmed date for the Solar Cycle 22/23 minimum, the range in the date of the smoothed cycle maximum is as follows:

January 1999	March 2000	June 2001

These dates were obtained using a range of dates in the time of minimum and a range of possible rise times. In general, larger cycles rise to maximum more quickly than weaker ones. For cycles with a predicted maximum of 160, the rise time is expected to be about 3.4 years (between the extremes of 2.8 and 4.3 years).

The determination of the precise "Shape" of Solar Cycle 23 in 10.7 solar flux and/or sunspot number is not currently possible. To provide a general shape for Cycle 23, profiles based on smooth "functional" forms derived from solar cycles 1-22, a profile from an average of recent large cycles (18, 19, 21 and 22), and a computed profile using a spectral analysis method based on cycles 5 through 22 were compared. All approaches agree closely with the consensus shape shown in Figure 3. This profile assumes that Cycle 23 minimum will be near September 1996. The smoothed maximum then occurs near March 2000, assuming a rise time of 3.4 years. The variability in the monthly 10.7 cm flux about the smooth curve is estimated to be plus or minus six at solar minimum, increasing to plus or minus 26 near maximum. The task force will review the prediction as Cycle 23 progresses, and will update it with new information. Observations between now and the end of 1997 will allow more precise timing of the solar cycle as the exact date of solar minimum becomes clear.

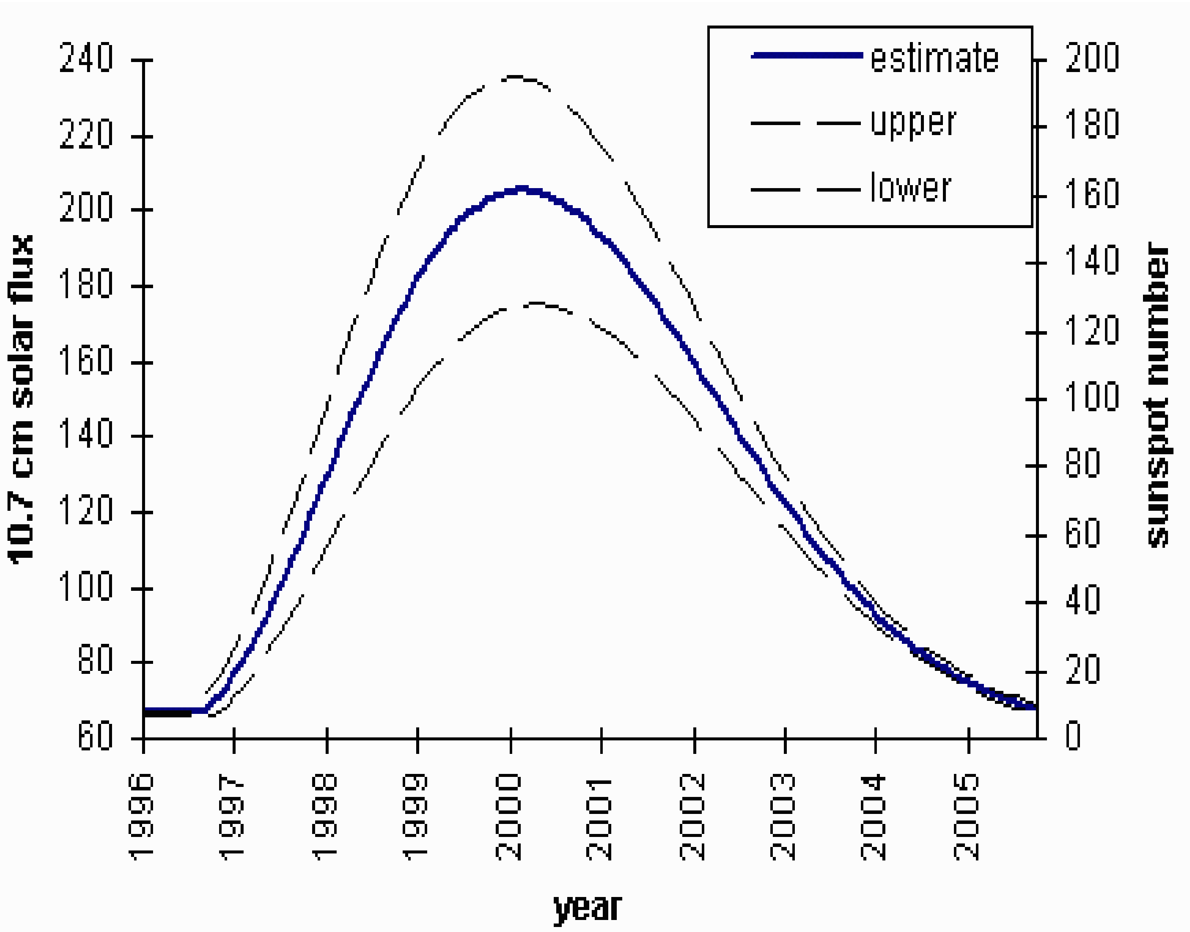

Figure 3: the estimated Cycle 23 profile of sunspot number and 10.7 cm solar flux.

Prediction of Geomagnetic Activity

The objective of the panel with regard to geomagnetic activity is to predict the approximate total number and annual number of significant geomagnetic disturbances during Cycle 23. This is a new objective that is not widely studied in the scientific community. Two types of forecasts were received: a climatological approach based on the 128-year record of the *aa* index, and a precursor approach that used the counts of disturbed days based on the A_p index, which has been archived since 1932. The two indices are similar since both are based on the daily summaries of the 3-hourly *K* indices derived at a network of geomagnetic observatories (Menvielle and Berthelier [1991] describe details of their derivation). The *aa* index is based on the observations at two nearly antipodal observatories (Canberra, Australia, and Hartland, United Kingdom), and is expressed in nanoteslas (nT). The A_p index, expressed in units of 2 nT, is derived from a larger network of geomagnetic stations but which includes the *aa* observatories. A quantitative comparison of the two indices [e.g. Mayaud , 1980] reveals that the conversion between them is on the order of A_p ~=0.8 *aa*. This conversion factor is taken into account in the results below.

Similar to solar cycle predictions, the climatological (statistical) forecasting approach uses the entire record of indices to extend the series, whereas the geomagnetic precursor technique does not rely on the whole record of activity but only on recently observed conditions. Both methods predict that the level of upcoming geomagnetic activity will be near the levels experienced in Cycle 22. The profiles of the activity differ, but both imply high levels during the years 1999-2005.

The climatological approach makes use of the secular trend since 1900 of an increase of approximately 15 nT per century (see Figure 2). Further, as noted by several researchers (e.g., Bartels [1963], Chernosky [1966]), the patterns of activity differ depending on whether the cycle number is even or odd-numbered. While all cycles have multiple-maxima, even-numbered cycles tend to have a broad maximum late in the declining phase of the solar activity cycle attributed to a favorable orientation of the solar dipole (positive polarity in the northern solar hemisphere) which is oppositely directed to Earth's dipole field. The climatological profile in Figure 4 (shown with the standard deviation calculated from median cycle statistics) is the median of the odd cycles. While this is appropriate for Cycle 23, as it turns out this result best reproduces the observed profiles (i.e., within +/- one standard deviation) of all recent solar cycles, even and odd. This result assumes that the beginning 13-month smoothed *aa* value for Cycle 23 repeats the value for Cycle 22 (17.2 nT). The expected number of disturbed days per year (daily *aa* >=100 nT) is shown on this plot and the total numbers for Cycle 23 are listed in Table 3. Following Feynman and Gu [1986], these numbers were determined from a quadratic fit of the relationship between the observed number of days with *aa* >=100 and the 13-month smoothed value of *aa* for all cycles. The likely error in the total number of disturbances of Table 3, for both *aa* >=50 nT and *aa* >=100 nT, is an underestimate of about 15%, based on the performance of the climatological method in predicting cycle 22. Year-by-year uncertainties, arising from the quadratic fit and median cycle statistics, are however as much as 50% to 100%, or more, for the number of days when *aa* >=100 nT. This, again, is consistent with the performance of the method in cycle 22. The highest errors occur in the most active years, when the method always underestimates the actual number of disturbances.

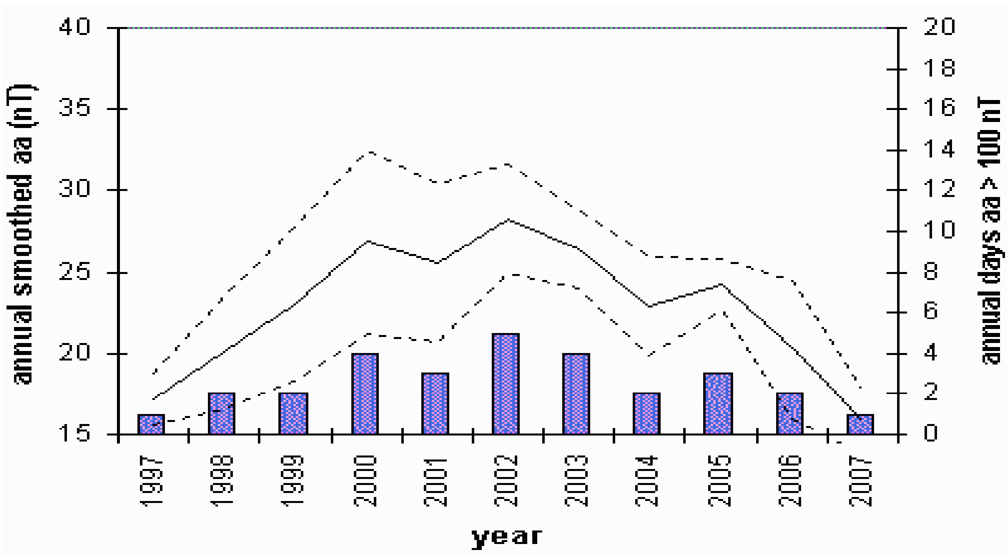

Figure 4: Climatological estimate of Cycle 23 *aa* profile (lines, left axis) and the annual number of geomagnetically disturbed days with *aa* >=100 nT (bars, right axis)

The precursor method uses the same relationship between solar and geomagnetic activity that has served well as a forecast of solar activity, in predicting the total number of disturbed days in the A_p index. To make this prediction it is necessary to know the amplitude of the following solar cycle Cycle 24. This is unknown at present and so has been taken to have a maximum sunspot number of 150, a reasonable estimate in view of the sequence of recent cycles close to this amplitude. The cycle profile of annual geomagnetic activity, however, must be assumed. At this time, because the forecast of solar activity is close to that observed for Cycle 22, it is assumed that the geomagnetic profile will mimic the cycle just past this result is shown in Figure 5. Table 3 lists the geomagnetic activity thresholds for *aa* and A_p, and the calculated number of occurrences during Cycle 23 for each method. The totals shown are comparable to the number of days of each type experienced in Cycle 22. The uncertainties scale with the assumed amplitude of Cycle 24 cycle sunspot number estimate of 200 would predict 700 days of A_p >=25, whereas an estimate of 100 would predict 500 days. In all cases, the expected number of very large storms (e.g., A_p >=100) is not well predicted owing to their rarity and the uncertainties are on the order of 100%.

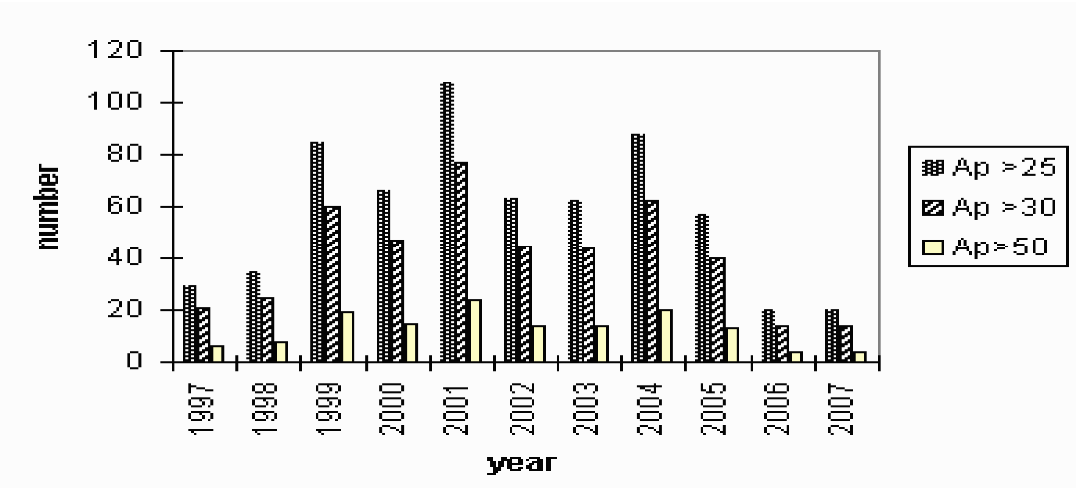

Figure 5: Precursor method estimates of geomagnetic activity during Cycle 23.

Table 3: Expected total numbers of disturbances in Cycle 23

Geomagnetic Index and Threshold A_p is expressed in units of 2 nT; *aa* is in units of nT	**Number of occurrences predicted by each approach**	
	precursor	climatolog.
A_p >=25	595	
A_p >=40; *aa* >=50	228	301
A_p >=50	133	
A_p >=80; *aa* >=100	44	29
A_p >=100	23	
A_p >=200	2	

Panel Recommendations for Future Solar Activity Studies

Criticisms of long-term solar cycle prediction focus on the thin physical foundation beneath such predictions and the limitations of the data used to define and extend solar and geophysical variability. The panel largely agrees with these criticisms, and offers the following recommendations to improve future studies:

- Long-term, consistent measurements of important solar and geophysical parameters should be continued and their quality maintained (e.g. calibration and sampling rates), including observations of 10.7 cm solar flux, international sunspot number, interplanetary fields and plasma near Earth, geomagnetic indices, and cosmic ray fluxes.
- Measurements of those parameters which may improve our understanding of solar cycles, such as solar vector magnetic fields, coronal mass ejections, stellar observations, and paleo cosmogenic data (e.g., ice cores, tree rings, etc.) should be continued.
- Prediction research should be supported and the scientific community encouraged to develop a fundamental understanding of the solar cycle that would provide the basis for physical rather than the present empirical prediction methods.

Conclusions

After examining a variety of methodologies used for predicting solar and geomagnetic activity in Cycle 23, the panel finds that a reasonable consensus is for a large solar cycle with a smoothed sunspot maximum of 160. This is comparable to the last two cycles, but is not expected to exceed Cycle 19, the largest cycle on record. While the month of solar minimum is yet to be determined, recent low levels of activity imply that the minimum is at hand, and will occur during the final months of 1996. If so, Solar Cycle 23 will most likely peak in early 2000. Likewise, geomagnetic activity during the cycle is expected to be comparable to that experienced in recent cycles, resulting in annual average levels among the highest in the 128-year *aa* record. The probability for severe geomagnetic storms will be the greatest during an extended period lasting from 1999 through 2005.

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