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Anomalies from Solar Events
Status of Solar Cycle 23 and Recent Effects on Technology and Humans

Solar Cycle 23 is now well into its declining phase. Sunspot numbers are falling monthly, but space weather still continues to affect many technologies. Emerging applications are finding that, even in the decline of the activity cycle, space weather is a significant factor for the proper function of their systems.

Anomalies from Solar Events
Status of Solar Cycle 23 and Recent Effects on Technology and Humans

J. Kunches, B. Poppe, K. Tegnell

NOAA Space Environment Center
325 Broadway
Boulder, CO 80305

1. Introduction

Solar Cycle 23 is now more than three years past maximum, and well into its declining phase. Sunspot numbers, 10.7 cm solar flux, and other indicators are reinforcing the opinion that Cycle 23's maximum era is over. This calming behavior should continue to mid 2007, projected to be the next solar minimum.

Although the more explosive types of activity – solar flares and coronal mass ejections – are now less frequent and impressive, the Sun still affects Earth's magnetosphere with yet another type of stimulus – the high-speed solar wind. During the decline of the cycle, the solar magnetic field organizes itself in a way that supports long-lived coronal holes – density voids with open magnetic field topology in the outer solar atmosphere -- that allow for the unimpeded escape of the solar wind from the Sun. This fast solar wind, with its embedded magnetic field, energizes Earth's magnetosphere. A consequence of the prolonged episodes of fast solar wind is large quantities of energetic (>2 MeV) electrons now occurring at geosynchronous orbit. These electrons can have a serious, deleterious impact, on satellites in orbit there. Energetic electrons cause deep dielectric charging of satellites, and can ultimately end the service life of a spacecraft. Serious satellite problems in 1994 – at the same point in the solar cycle – were diagnosed to be due to the cumulative impact energetic electrons.

2. Solar Cycle Update

Solar Cycle 23 attained its maximum, as measured by sunspot numbers, in April 2000. Recent solar cycle sunspot number amplitudes are given in Table 1. The smoothed sunspot number of 120.9 fell short of the predictions to be near 160. By way of contrast, Cycle 19, which peaked in 1957, was the largest ever recorded; Cycle 21 which peaked in 1979 was the second largest on record; and Cycle 22 was the 4th largest ever seen. Even the "odd-even" rule of thumb has been broken. This venerable rule, which says that an odd numbered cycle is larger than the preceding even numbered cycle, has persisted through six pairs of cycles back to Cycle 8/9 around 1850. Table 1 (Thompson, 2002) lists aspects of recent solar cycles.

Cycle Number	Date of Cycle Start	Date of Cycle Maximum	Amplitude (Sunspot Number)	Length (Years)
17	1933.8	1937.4	119	10.4
18	1944.2	1947.5	152	10.1
19	1954.3	1957.9	201	10.6
20	1964.9	1968.9	111	11.6
21	1976.5	1979.9	165	10.3
22	1986.8	1989.6	159	9.7
23	1996.3	2000.3	121	?

Table 1: Recent solar cycle parameters.

Figure 1 gives the history, over the past few cycles, of large solar x-ray flare occurrences. Although those events cluster near solar maximum, they do occur at a decreasing frequency at other points in the cycle. Major geomagnetic storm activity, as depicted in Figure 2, shows a bimodal behavior with a secondary peak in the decline of the cycle. This later pulse belies the notion that geomagnetic storms track with the sunspot counts. The shading in the figures allows the reader to see the same point in each of the cycles shown.

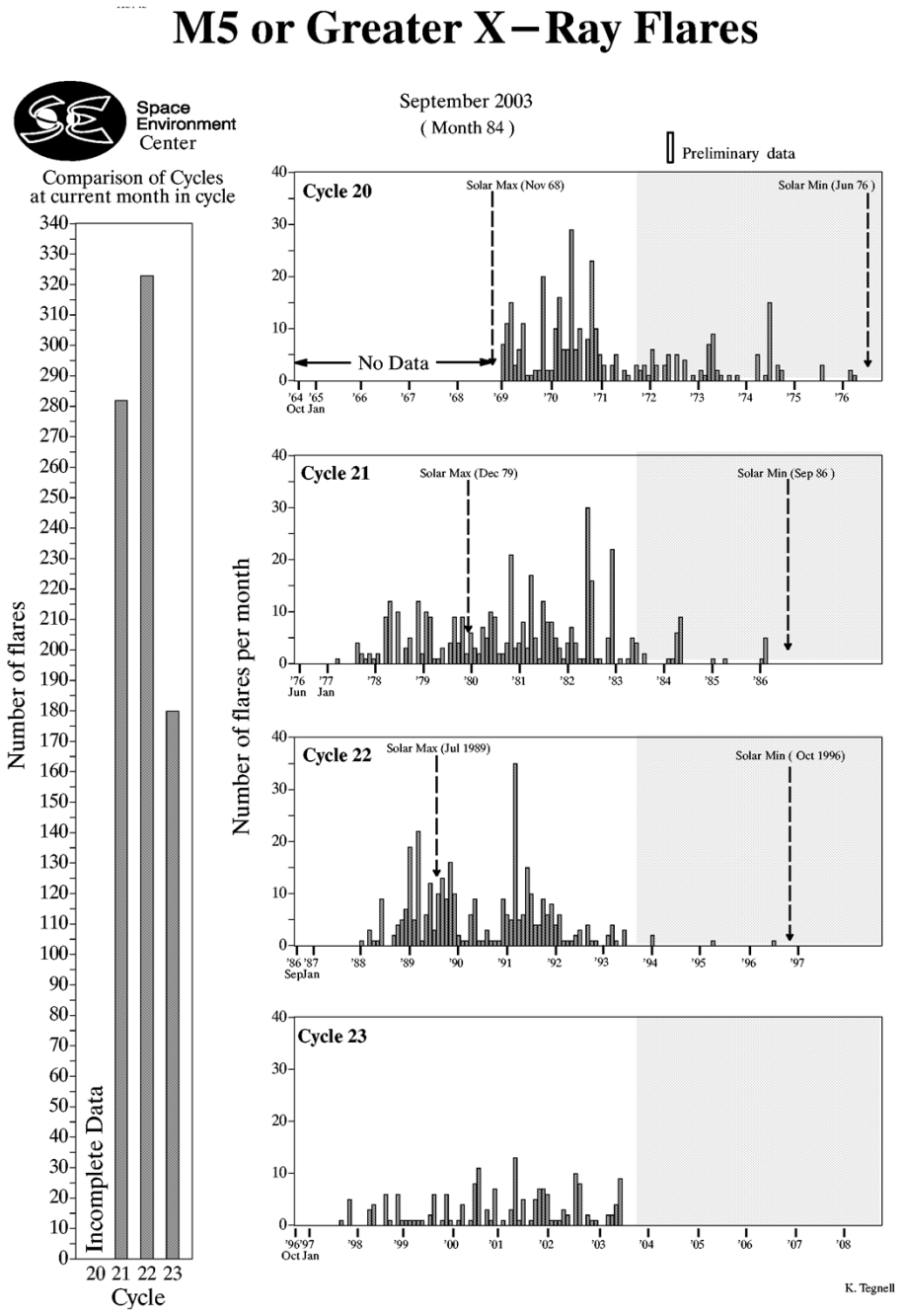

Figure 1: The occurrence of Class M Flares, through September 2003. Note the histogram at left, comparing the M Flares from Cycles 21-23, with Cycle 23 being the least productive.

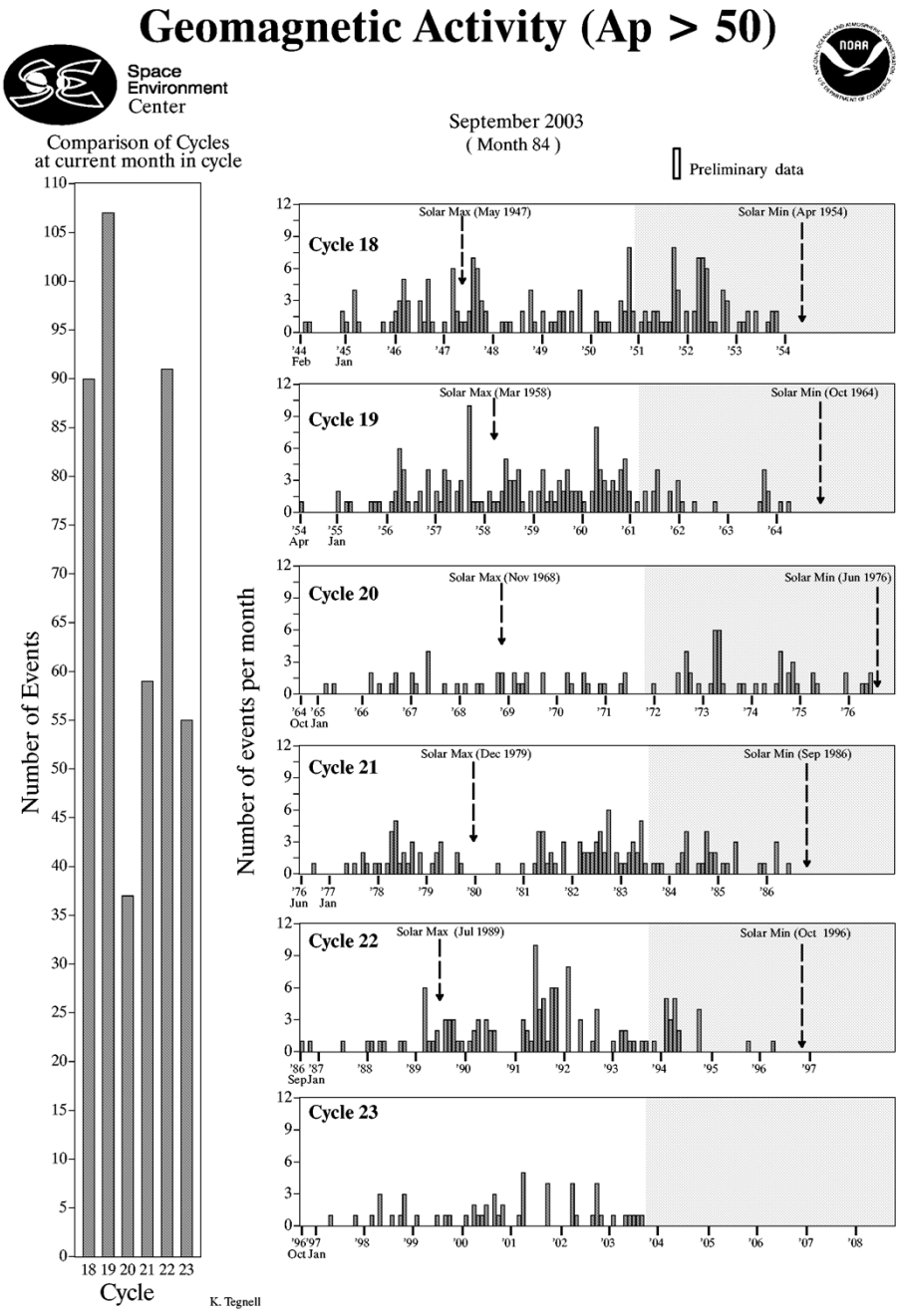

Figure 2: Geomagnetic Ap >50, through September 2003. Ap >50 is a major to severe magnetic storm. Cycle 23 was less eventful than all cycles except Cycle 20.

Figure 3 is a summary of the proton events occurring in Cycles 20-23. It is interesting to note that Cycle 23, in terms of the number of events, was the most prolific cycle on record. Proton events have a strong impact on satellite operations, degrading solar panels and interfering with various types of optical systems.

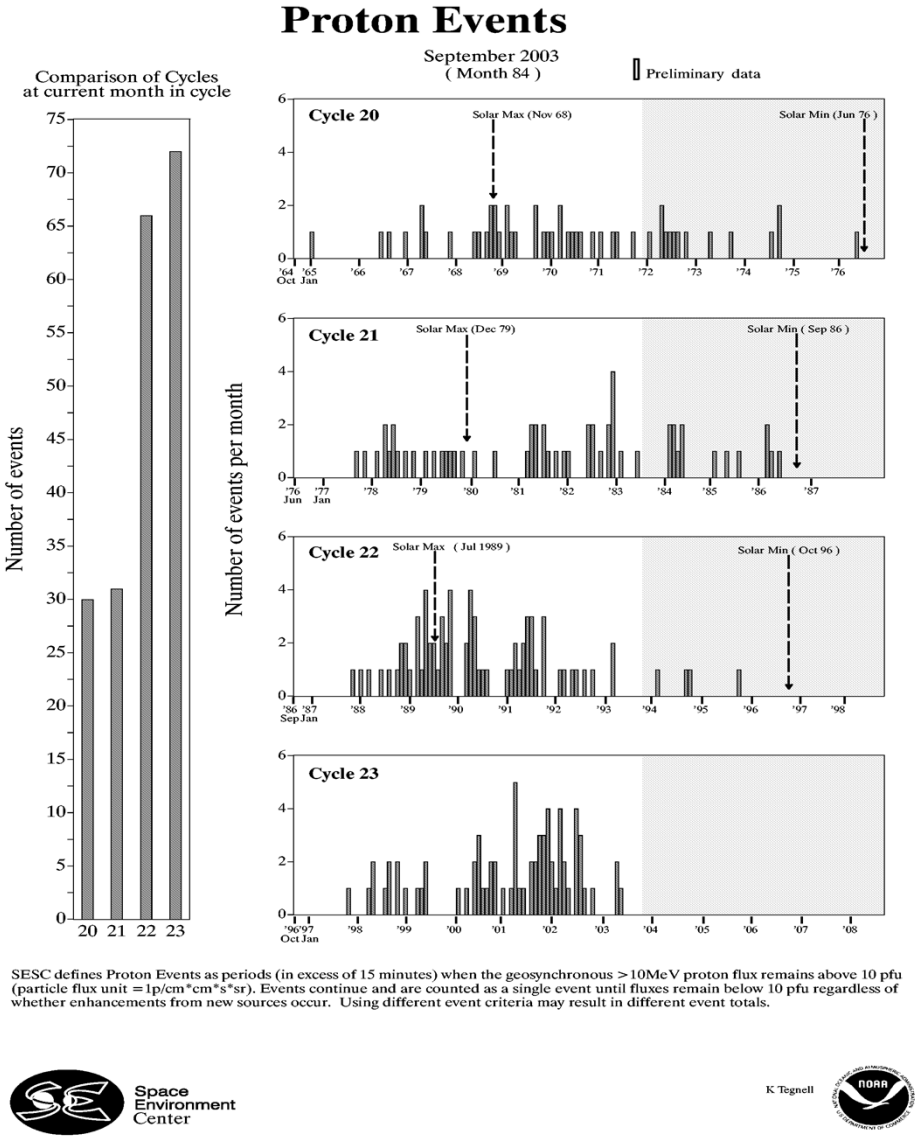

Figure 3: Proton events through September 2003. Cycle 23 has seen the largest number of such events.

3. Space Weather Week

A sampling of current activities and emerging technologies was taken at the recent Space Weather Week, held at NOAA SEC in Boulder Colorado in May 2003. This meeting provided a forum for providers and users of space weather services to communicate issues related to space weather. There were over 300 participants, 50 oral presentations and 75 posters given during the Space Weather Week. Some of the high points from a few of the presentations were:

4. Space Weather Agency Activities

RDML Thomas Donaldson, head of the US Naval Meteorology and Oceanography Command, explained how important space weather is to their communications between fleet commanders and front-line units, and to the satellite-guided systems operated in the field. There are many instances of communication disruptions and GPS error impacts caused by ionospheric disturbances.

BG David Johnson, HQ USAF/XOW said that every USAF aircrew is now briefed on space weather impacts.

5. Precision GPS and Communications

Improved model of the ionosphere would be a great advance for Real-Time Kinematic GPS surveys. It would allow a much faster resolution of the ambiguities that result from using GPS phase measurements, resulting in cost savings.

High Precision GPS surveys are being conducted at Prudhoe Bay to model the effects of the water flood program used to keep the pressure in the sub-surface gas cap. Disturbed space weather conditions have impacted work there, but to a much lesser extent recently.

Environmental conditions related to the occurrence of the scintillations in the ionosphere affect-and sometimes eliminate-the use of GPS at various parts of the world.

Space weather activity, above critical threshold values of F10.7 and Ap, was problematic for Differential GPS Positioning used in precise geophysical operations offshore, near West Africa and Eastern South America.

A new technique has been developed relating absorption and ionization during times of increased energetic particle fluxes in the polar cap.

6. Satellite Drag

Continuing solar radio monitoring is useful and relevant for the foreseeable future; it's cheap and reliable and can give useful solar radio burst information.

The High Accuracy Satellite Drag Model (HASDM) being developed by the USAF computes "real time" upper atmospheric neutral density variations. This can be used to help identify lost satellites, and orbit predictions can be improved by predicting the global temperature field with respect to solar index predictions.

7. Electric Power Grids

Real-time electricity market price is affected by even moderate geomagnetic storms. The estimated average impact is a non-trivial 4.5% of the real-time Pennsylvania, New Jersey, Maryland (PJM) power grid price. This was based on a study between June 1, 2000 to December 31, 2001, on the hourly prices and loads, this works out to approximately $650 million.

A study on US power grid vulnerability showed that a disturbance in the 300-600 nT/min range would have serious impacts on the grid. Within the civilian power market, space weather caused 55 % of the transmission constraints in 2001.

8. Trapped Radiation and Magnetospheric Plasma

Trapped magnetospheric plasma has a wide range of impacts on spacecraft and instrumentation. The Space Environmental Effects Working Group (SEEWG) under the Space Technology Alliance recommends government investment strategies for research and development that will lead to understanding and mitigation of space environment effects. A recent conference held in November 2002 focused on space environmental effects on large imaging systems.

Recent work is providing statistical information on the kinds of environment-related spacecraft anomalies that occur most often and are of greatest concern. New research and modeling are leading to improved predictions of ring current and radiation belt particles.

10. Solar Radiation Storms

Solar and galactic radiation presents a hazard to aircrew and passengers on flights at high altitude and high latitude. The FAA reported a new product for alerting on these events developed by the FAA/CAMI group and made available to the FAA and airlines.

NASA Space Radiation Analysis Group reported that a geomagnetic cutoff model used to predict timing and intensity of high-dose rate conditions during solar proton events has been successfully applied as an operational support tool to support human space flight.

11. Modeling, Metrics, and Transition

Numerous large, multi-institution research efforts are underway and making impressive progress on modeling the space environment from the Sun to Earth. These models require individual modules that contain the important physical processes for each region, and then

must couple and allow the interaction among the different regions. Numerical techniques, such as adaptive mesh refinement, are being utilized successfully to optimize the execution of the large numerical
codes. Data assimilation is also being applied successfully to model the dynamics of the ionosphere, where good spatial coverage of near real-time data is available.

In addition to the development of space environment models, excellent progress is also being made in ensuring that models become available for widespread scientific use and validation through the interagency supported Community Coordinated Modeling Center located at NASA's Goddard Space Flight Center. Activities are also moving forward on the transition of research developments into operations, and on the verification of operational products.

12. Service Providers

The International Space Environment Service (ISES) is concerned with the provision of space environment products and services to assist users to reduce the impact of space weather on activities of human interest.

The Commercial Space Interest Group was established in 2002 to foster growth in Operational Space Weather Services.

The AGU launched a new journal "Space Weather: The International Journal of Research and Applications." See http://www.agu.org/journals/sw/ for information.

Through Websites, workshops, traveling exhibits, and teacher training, many colleagues are contributing to improving education.

Space Climate

Solar Cycle 23 began in May 1996, and peaked in April 2000. It has been a very average cycle, the fifth largest in past century but second smallest in past six cycles. It has produced energetic proton events nearly as large as cycle 22 and much larger than cycles 20 and 21.

Compelling evidence for a 10% anthropogenic thermospheric density decline over the last two decades from the analysis of satellite drag.

Cautionary examples of typical pitfalls in trend detection from environmental data and the importance of data quality and uniformity reminded us that instrumental and human errors and overall variability can be revealed in the context of long-term ionospheric sounding data sets.

13. Solar Observations and Data

The Ramaty High Energy Spectroscopic Imager (RHESSI) mission X-ray images and spectra of solar flares is primarily a scientific mission, with very exciting discoveries and results,

there is great potential for applying the scientific results to more practical realm of space weather and the prediction of geoeffective solar phenomena.

NOAA/GOES 12 SXI is operating nominally and is generating an image of the sun every minute in x-rays. The operational products are extensive and include flare location and an image display and analysis package.

The upcoming NASA Stereo mission will send probes ahead of and behind Earth, but in Earth's orbit, to obtain a stereo view of the sun and heliosphere, and especially a stereo view of CMEs that have the potential of impacting Earth.

14 References

Solar Cycle Number 23 – A Progress Report, R. Thompson, *GPS Solutions*, Vol 6, No. 1-2, 2002, pp 121-123. Springer-Verlag, Berlin.