

Solar and Solar Wind Disturbance Predictions

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14. ABSTRACT A prediction of 75, a relatively very low number, has been made for the peak sunspot number for solar cycle 24. Direct measurements of the solar wind magnetic field strength and speed became routinely available in the 1960s. The Interdiurnal Variability Index has been used to reconstruct the magnetic field strength of the solar wind, thereby extending the data back for a total of about 125 years. With these results and the Interhourly Variability Index, the speed of the solar wind has been determined for the same period of time. Other results include the establishment of bench marks for the extreme limits of solar-terrestrial activity and validation of the Proton Prediction Study tool for short term alerts of solar particle events.					
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1. INTRODUCTION

The principal research objectives of this in house work unit were to provide reliable prediction and specification of solar and solar wind disturbances, and the hazards they pose to the operations/lifetimes of AF/DoD ground and space-based assets and operations. Solar phenomena that require prediction include flares (which cause short wave fades and natural jamming of radar systems), solar energetic particle events (single event upsets, solar panel and sensor damage, and human radiation threat), and geomagnetic storms (satellite drag).

Significant progress was made in each of the three principal areas (reflecting the three basic types of solar emissions: electromagnetic, particle, and solar wind) during this seven year effort although, reflecting both the change in composition of the scientific team and the nature of research itself, several of the results obtained were not anticipated at the outset. In particular, pioneering results were obtained in the area of space climate, the long-term baseline from which space weather is predicted. The potentially most important new finding was prediction of the peak sunspot number for solar cycle 24 [estimated peak sunspot number (SSN) of ~75 for the ~2012 solar maximum]. A second key result involved the reconstruction of solar wind magnetic field strength and speed for the last ~125 years. Additional significant work included establishment of bench marks for the extreme limits of solar-terrestrial activity (flares, particle events, geomagnetic storms, and aurora) and validation of the Proton Prediction Study tool for short term alerts of solar particle events. These main findings are summarized in this report. In addition to these salient results, additional topics addressed in papers published under this work unit include: real-time forecast skill scores, transit times of interplanetary shocks, radiation dose for air crews, “rogue” particle events, and source regions of solar particle events. A complete list of all papers attributed to this work unit is given in the Appendix.

2. REVIEW OF MAJOR RESEARCH ACCOMPLISHMENTS

2.1 Prediction of the Peak Sunspot Number of Solar Cycle 24

Predicting the peak amplitude of the sunspot cycle is a key goal of solar-terrestrial physics. The “precursor method” is the preferred technique for making such predictions. Devised by *Schatten et al. (1978)*, it is based on the solar dynamo model in which large-scale polar fields observed during the decline of an 11-yr solar cycle are converted to toroidal

(sunspot) fields observed during the maximum of the subsequent cycle. At the time it was first postulated, direct observations of solar polar magnetic fields were only available for a single solar cycle. Thus early precursor-type predictions were necessarily based on proxy data such as geomagnetic observations from which polar field strengths might be plausibly inferred. By 2005, observations of the solar polar fields were available for enough solar cycles that a correlation plot could be constructed between the field strength at the end of one cycle and the peak sunspot number (SSN) of the subsequent cycle. This correlation could then be used to make a prediction of the coming cycle once the field strength of the preceding minimum had been determined. Such a prediction was made by *Svalgaard, Cliver, and Kamide (2005)*.

The basic measurements underlying the prediction are given in Figure 1 where the difference between the polar field strengths for the northern and southern solar poles, as measured by two separate observatories [Wilcox (WSO) and Mt. Wilson (MWO)] are plotted as a function of time from 1970-2005. The negative of this curve is also plotted to facilitate comparison between the solar cycles; in this representation, the diameter or size of the “circle” is proportional to the peak SSN of the subsequent cycle. Thus the vertical diameter of the circle centered on 1985 indicates the peak SSN of the 1990 solar maximum and, in a true forecast sense, the height of the half circle in 2005 yields the peak of the coming solar cycle.

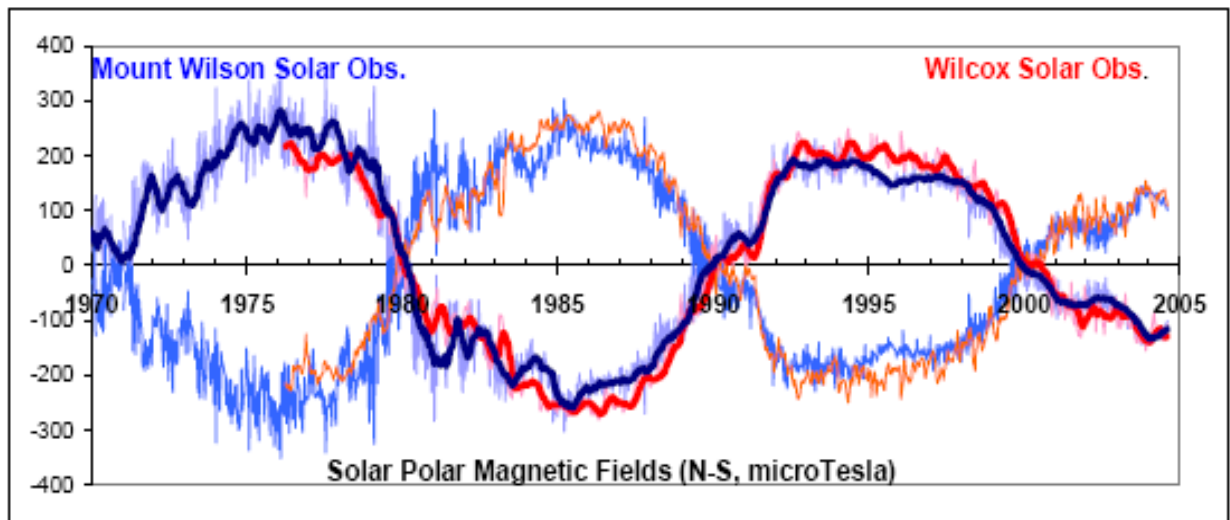


Figure 1. Time Variation of the Solar Magnetic Dipole Moment. MWO data is shown with bluish colors. WSO is shown with reddish colors. Heavy lines show 12-month running means of the N-S difference (from *Svalgaard, Cliver, and Kamide, 2005*).

Figure 2 illustrates the precursor technique for the four cycles displayed in Figure 1 as well as for two earlier cycles for which the solar polar field measurements were of lower confidence. For each case the polar field strength at solar minimum (red circles, with the size of the circle reflecting the uncertainty of the measurement) serves as a precursor/predictor for the amplitude (peak SSN) of the following solar maximum.

Based on Figure 1, *Svalgaard, Cliver, and Kamide (2005)* predicted that cycle 24 would have a peak SSN of ~ 75 , making it the smallest cycle in ~ 100 years. For comparison, solar cycle 23 which reached its maximum in 2000 had a peak SSN of 121, while cycles 21 (maximum in 1979) and 22 (maximum in 1989) both had peak SSNs of ~ 160 . In contrast with the low peak SSN prediction of *Svalgaard, Cliver, and Kamide (2005)* for cycle 24, *Dikpati, de Toma, and Gilman (2006)* used a flux-transport dynamo model to predict that cycle 24 will be larger than average, with a peak SSN 30-50% higher than that of cycle 23 (i.e., peak SSN = 155-180).

This difference has sparked much commentary (e.g., *Clark, 2006; Wang and Sheeley, 2006; James, 2007*) and now it is up to the Sun to decide. Before the cycle 24 maximum

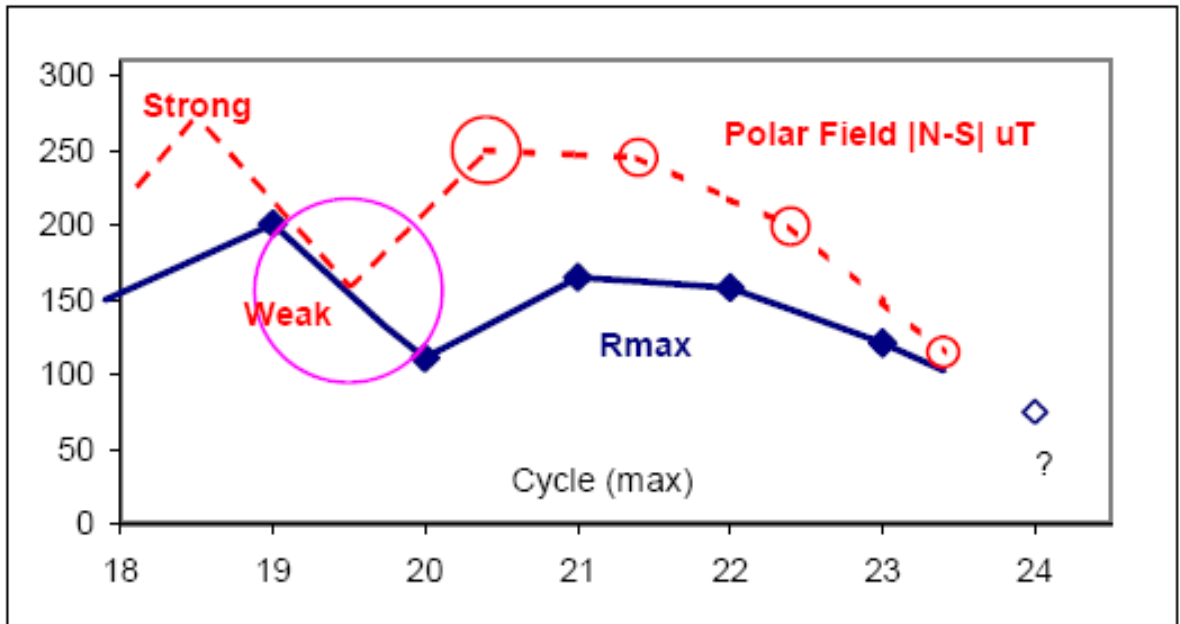


Figure 2. Illustration of the Precursor Method Based on Measured Solar Polar Fields for Solar Cycles 18-24. In each case the measurement of these fields at the minimum following a given cycle (dashed red line and circles) serves as an indicator of the peak SSN of the subsequent cycle (solid blue line and diamonds).

(estimated for ~2012) occurs, however, a panel convened by NASA to make an official prediction will need to choose between the two divergent predictions. As of April 2007, the panel was evenly split and decided to wait until the Sun comes closer to its minimum state (expected to be reached during 2008) before issuing its forecast.

2.2 Space Climate

2.2.1 LONG-TERM (~1890-PRESENT) RECONSTRUCTION OF THE SOLAR WIND MAGNETIC FIELD STRENGTH AND SPEED

Direct measurements of the solar wind only became routinely available in the mid-1960s. How representative are measurements made during the last ~40 years of long-term (at least centuries) solar wind conditions? To address this question, geomagnetic data, which are reasonably complete back to ~1840 and which exist sporadically for about 100 years before that, were used to extend our knowledge of solar wind conditions back in time. To first order, geomagnetic activity is driven by the solar wind magnetic field strength (B) and speed (V). The approach used was to derive two new long-term geomagnetic indices [the Interdiurnal Variability (IDV) Index (*Svalgaard and Cliver, 2005*), and the Interhourly Variability (IHV) index (*Svalgaard and Cliver, 2007b*)] with different dependencies on these two solar wind parameters. The preferred time scale for these indices is one year, but, with caution, they can be derived for the 27-day solar rotation interval. The key breakthrough in this effort was Svalgaard's realization that the IDV index, defined as the unsigned difference between an hourly average in nT of a field component for a given hour near local midnight on two consecutive days (with the value assigned to the first day), was highly correlated with B and essentially independent of V when daily values were averaged over a year (Figure 3). Thus once IDV is determined, as can be done with readily available data back to 1872, the yearly-averaged values of the B parameter are given by the correlations in Figure 3. The second index used, IHV, is mechanically derived for a given geomagnetic element from hourly values or means for a given station as the sum of the unsigned differences between adjacent hours over a seven-hour interval centered on local midnight. The index is derived separately for stations in both hemispheres within six longitude sectors spanning the Earth

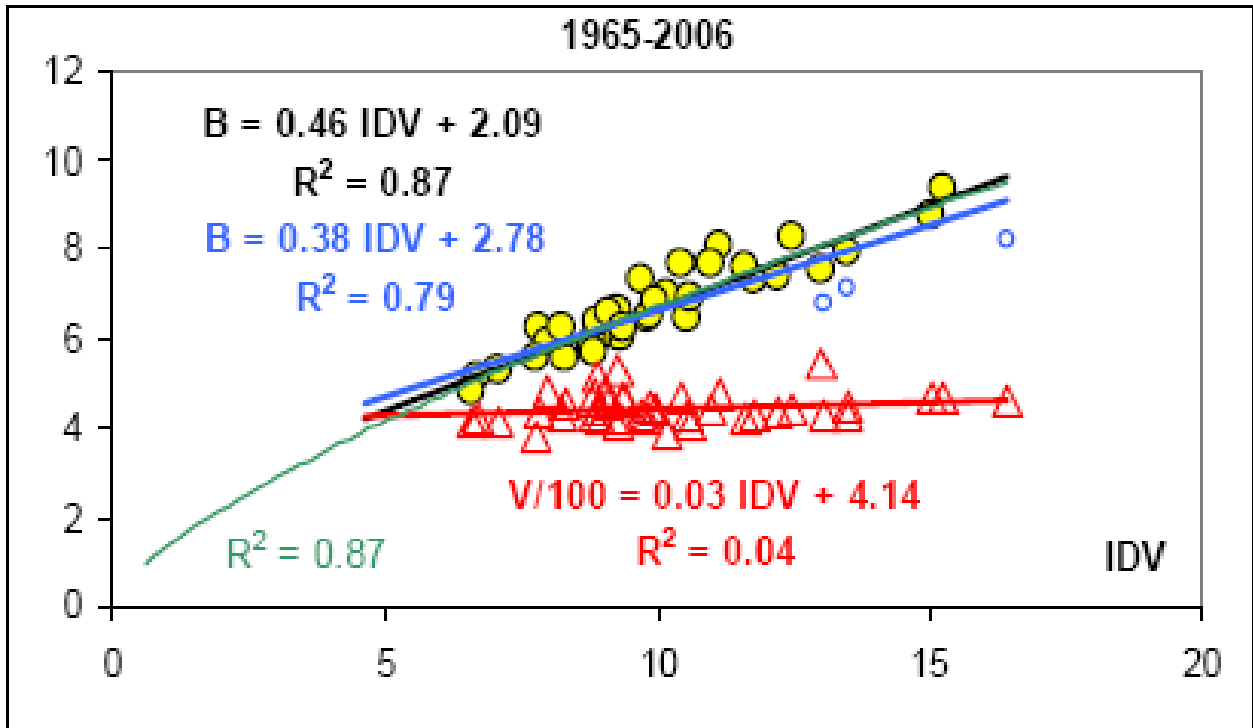


Figure 3. Dependence of the IDV Index on B and V During the Space Age (from *Svalgaard and Cliver, 2007a*).

using only local night hours. As is the case for the IDV index, IHV is intended as a long-term index with a minimum time scale of 27-days. The use of only nighttime hours in the derivation of both the IDV and IHV indices circumvents the central challenge of constructing geomagnetic indices (*Bartels, 1932; Mayaud, 1980*) – the separation of solar-wind induced activity from that due to the regular variation of the ionosphere driven by solar ionizing radiation.

Like other mid-latitude range indices, the IHV amplitude is proportional to BV^2 (e.g., *Svalgaard, 1977; Feynman and Crooker, 1978; Feynman, 1980*). Thus, once yearly averages of IHV are constructed (now done from 1890 to the present), it is a simple matter to substitute annual values of B obtained from the IDV index, and solve for yearly averages of V. The results of this exercise are shown in Figure 4. The long-term reconstruction of B in this figure (from *Svalgaard and Cliver, 2005*) differs markedly from a reconstruction obtained from the geomagnetic aa index (*Mayaud, 1972*) by *Lockwood, Stamper, and Wild (1999)*, sparking an exchange in the literature between *Lockwood et al. (2006)* and *Svalgaard and Cliver (2006)*. A more recent reconstruction by *Rouillard, Lockwood, and Finch (2007)*, however, shows substantial agreement between the two groups for all but the earliest years

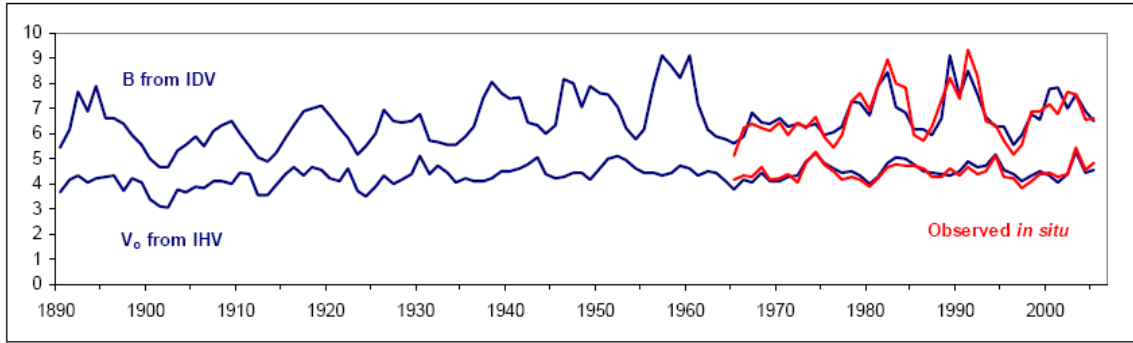


Figure 4. Annual averages of B and V ($V_O = V/100$) for 1890 to the present as derived from the IDV and IHV indices (blue lines) and as measured directly (red lines) since 1965 (from *Svalgaard and Cliver, 2007b*).

(pre-1910) of the time series. Both sides are in agreement with the view, first put forth by *Svalgaard, Cliver, and Le Sager (2004)*, that the calibration of the aa index is inhomogeneous, with values artificially low (by about 3 nT) before 1957.

2.2.2 EXTREMES OF SPACE WEATHER ACTIVITY

The study of space climate involves both long-term average behavior, such as that shown in Figure 4, and variations about those long-term averages. Of particular interest are the extreme limits of variability, the “100-yr floods” of space weather. *Cliver and Svalgaard (2004)* examined the great solar-terrestrial disturbance of 1859, by remarkable coincidence associated with the first solar flare ever reported (*Carrington, 1860*), as a gauge of extreme space weather activity. Using the limited data available for the 1859 event, they compared it with more recent severe space weather in an attempt to set benchmarks for flare size, particle intensity, solar wind speed, geomagnetic storm intensity, and low- latitude auroral extent. By comparing the magnetic crochet (a type of sudden ionospheric disturbance apparent in magnetometer data) associated with the solar flare on 1 September 1859 with those associated with recent great flares, they were able to infer a soft X-ray intensity class of $> X10$, conservatively placing it among the top ~ 100 events of the last ~ 150 years. The approach is illustrated in Figure 5, which shows a comparison of soft X-ray and geomagnetic data for two large flares in 2003. Table 1 summarizes this comparison for several large flares including the 1859 event.

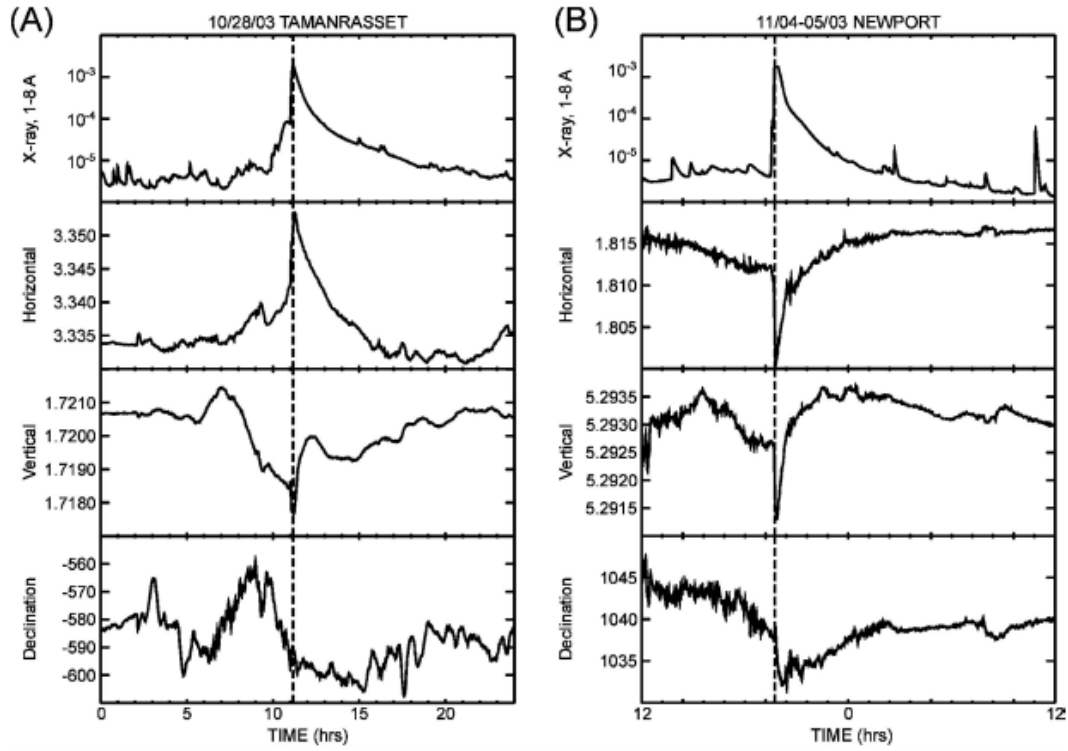


Figure 5. Large (> 100 nT) Magnetic Crochets (also Referred to as Solar Flare Effects or Solar Flare Effects) on (a) 28 October 2003 and (b) 4-5 November 2003. In each case the soft X-ray burst is shown with the magnetometer traces for the station with the largest H-component deflection (from *Cliver and Svalgaard, 2004*).

McCracken et al. (2001a,b) have used nitrate composition in ice cores to obtain a list of large solar energetic particle (SEP) events occurring from 1561-1950, extending the list to 1994 by using ionospheric and satellite data. Table 2 gives a list of the largest events during this period in terms of the >30 MeV proton fluence. The >30 MeV fluence of the 1859 event was three times greater than that of any event directly observed during the space age, striking a cautionary note for spacecraft designers.

Tsurutani et al. (2003) recently reanalyzed the Colaba (India) horizontal intensity record for the 1859 event and obtained a Dst index of ~ 1750 nT, a factor of three greater than that obtained for any event during the space age. Subsequently various arguments (see *Cliver and Svalgaard, 2004*), including the reduced (10-minute vs. normal 1-hr) time scale on which their Dst index was based, have been raised to indicate that the 1859 storm was not markedly larger than the top tier of subsequent great storms.

Table 1. Outstanding Solar Flare Effects at Mid-latitudes Identified in a Literature Search for Events from 1936-1968 and from Associations with >X10 Soft X-ray Flares, 1984-2003 (from *Cliver and Svalgaard*, 2004).

Date	1–8 Å Class	Magnetometer station	Zenith angle (°)	SFE amplitude (nT)
04 Nov. 2003	X28	Newport	63	115
28 Feb. 1942	–	Eskdalemuir	63	112
28 Oct. 2003	>X17	Tamanrasset	36	111
01 Sep. 1859	–	Greenwich	44	110
15 Jun. 1991	>X12	Hyderabad	22	95
06 Jun. 1991	>X12	Guam	20	90
15 Apr. 2001	>X15	Tamanrasset	34	85

Table 2. Large Solar Energetic Proton Events, 1859-2000^a (from *Cliver and Svalgaard*, 2004).

Date ^b	>30 MeV SEP fluence (10 ⁹ pr cm ⁻²)
Aug.–Sep. 1859	18.8
1895	11.1
Nov. 1960	9.7
1896	8.0
1894	7.7
1864	7.0
Jul. 2000	6.3
1878	5.0
Aug. 1972	~5

^aMcCracken *et al.*, 2001a; see text for sources of data.

^bOnly year given for events without identified candidate sources.

Cliver and Svalgaard (2004) concluded that while the 1859 event had close rivals or superiors in each of the categories considered, it was the only documented event of the past ~150 years that appeared at or near the top of all of the lists. As a final point of interest, it can

be seen in Table 2 above that three of the five largest SEP events since 1859 occurred during the mid-1890s, a time of relatively low sunspot activity (cycle 13 peak SSN = 88; see *McCracken*, 2007, for a possible explanation for this unexpected behavior) while Table 5 in *Cliver and Svalgaard* (2004) shows that two of the eight strongest geomagnetic storms during the past ~150 years occurred in 1903 and 1909 during solar cycle 14 (peak SSN = 64). Thus a weak sunspot cycle, which we are approaching if the prediction of *Svalgaard, Cliver, and Kamide* (2005) bears out, is no guarantee of a reduced space weather hazard, particularly when one considers that a single large episode of events [e.g., August 1972, March 1989, October-November 2003 (*Webb and Allen*, 2004)] can dominate effects for an entire solar cycle.

2.2.3 SEASONAL VARIATION OF GREAT GEOMAGNETIC STORMS

Crooker, Cliver, and Tsurutani (1992) noted that great geomagnetic storms favored the equinoxes (March and September) and were conspicuously absent during the solstices (June and December). This is demonstrated using the A_p^* index in Figure 6; note that no storms with $A_p^* \geq 100$ occurred during the month of December from 1932-1989. While this pronounced variation, in and of itself, can be exploited by space weather forecasters, high-confidence forecasts require an explanation, or at least a quantitative model, of this behavior. An explanation was provided by *Svalgaard, Cliver, and Ling* (2002), based on the seasonal/universal time dependence of geomagnetic activity on the dipole tilt angle (ψ , the angle between the solar wind flow direction and Earth's dipole axis) apparent in Figure 7. The pattern in the figure can be fitted with the expression $(1 + 3 \cos^2 \psi)^{2/3}$ (*Svalgaard*, 1977). If this dependence is removed, or normalized, from the geomagnetic data time series, *Svalgaard, Cliver, and Ling* (2002) showed that about 75% of the annual variation in great storms disappears, roughly consistent with the viewpoint that the ψ dependence accounts for about two-thirds of the seasonal variation, with various other second order factors accounting for the remainder (*Cliver, Kamide, and Ling*, 2000; *Petrukovich and Zakharov*, 2007). This detailed modeling of the relationship between the solar wind and geomagnetic activity is necessary to be able to predict the response of the magnetosphere, and issue short-term warnings of major storms, from observations of solar wind parameters upstream of the Earth.

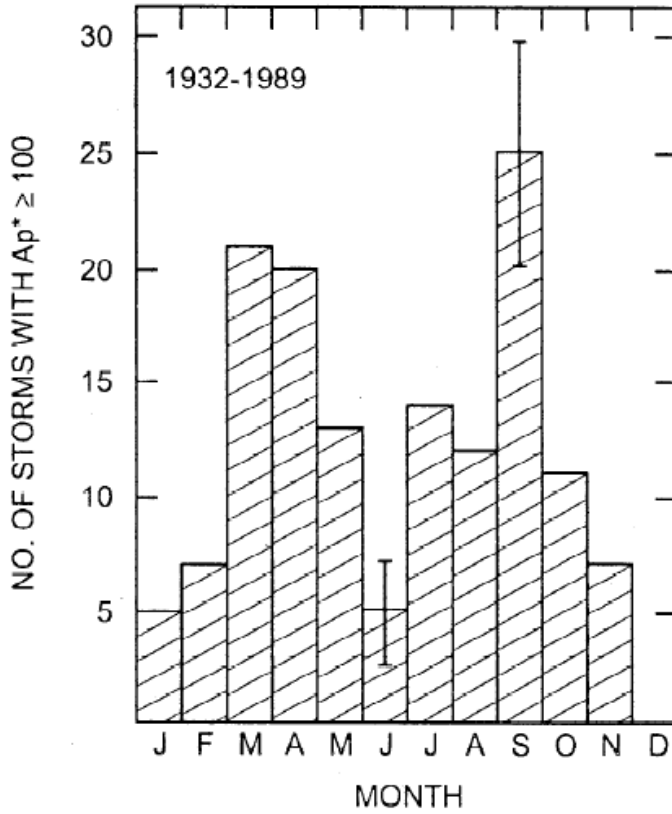


Figure 6. The Semiannual Variation of the Occurrence of Great Geomagnetic Storms (adapted from *Crooker, Cliver, and Tsurutani, 1992*).

2.3 Validation of the Proton Prediction System For Short-Term Warnings of Solar Energetic Proton (SEP) Events

Forecasting SEP events has been a long-term priority of the solar section in the Space Weather Center of Excellence. SEP forecast studies were pioneered by Center of Excellence emeriti D.F. Smart and M.A. Shea (*Smart and Shea, 1979, 1989, 1992*), who used solar flare observations to predict the occurrence, timing, intensities, spectra, and elemental composition of SEP events at 1 AU with energies $> 5, 10$, and 50 MeV, as well as other SEP applications such as terrestrial dose rates and ionospheric absorption. Recently, *Kahler, Cliver, and Ling (2007)* evaluated the Proton Prediction System's probability of detection (PoD) and false alarm rate (FAR) for SEP events meeting the joint USAF/NOAA SEP flux (J) prediction threshold of $J(>10 \text{ MeV}) \geq 10$ proton flux units (PFU), for a time interval lying outside of that providing the data on which this prediction system was developed. A correlation plot of observed vs. predicted > 10 MeV SEP intensity for 78 soft X-ray flares with intensity class $\geq$

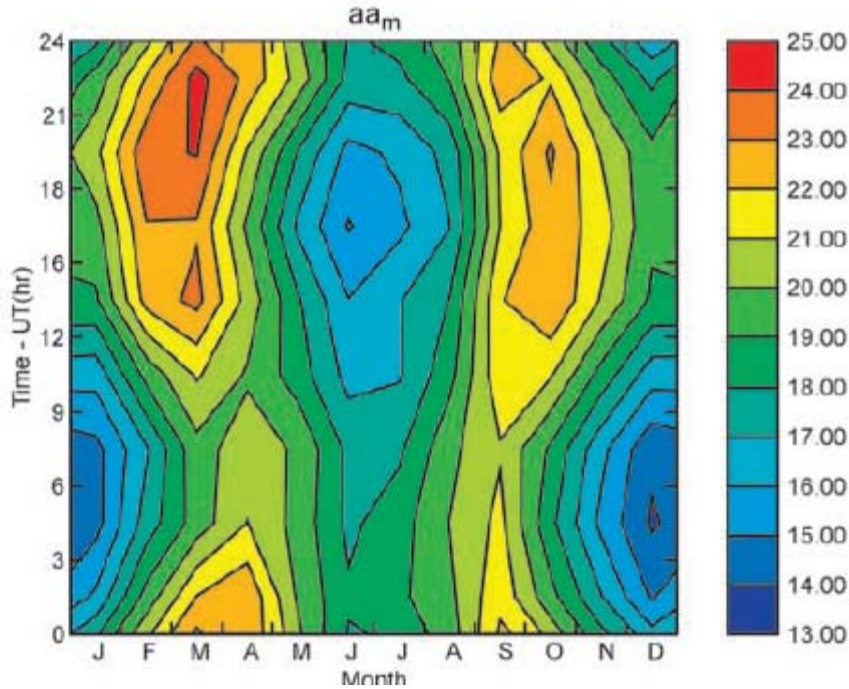


Figure 7. Seasonal/universal Time Variation of the Geomagnetic aa_m Index (from Svalgaard, Cliver, and Ling, 2002).

M5 occurring during the years 1997- 2001 is given in Figure 8. For the five year interval, *Kahler, Cliver, and Ling* obtained a PoD of 43% (18/42) and a FAR of 50% (18/36).

These statistics are comparable to those recently reported by *Balch* (2007) for the PROTONS prediction technique currently in use at the Joint Forecast Center (PoD = 57%, FAR = 55%).

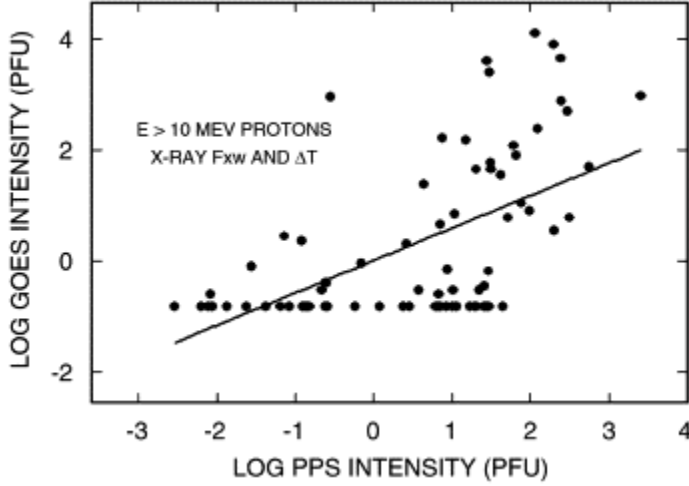


Figure 8. Comparison of the GOES peak ($J > 10$ MeV) SEP intensities with the Proton Prediction System predictions for $78 \geq M5$ flares (from *Kahler, Cliver, and Ling, 2007*).

A SEP forecast effort involving a collaboration with the Institute for the Physics of Interplanetary Space of the Italian National Institute for Astrophysics was initiated to improve on the above forecast statistics. Developmental results to date are encouraging and this work will be completed and extended in the subsequent 6.2 in house work unit.

3. CONCLUSION

Work accomplished under this work unit broke new ground on SSN prediction and on the historical reconstruction of the solar wind. It highlighted the challenge to improve SEP forecasts and initiated an effort to do so. It did not address the most formidable problem of applied solar physics – flare prediction. Recent improvements in patrol observations (specifically, the Optical Solar Patrol Network telescope at Sacramento Peak Observatory and the Solar Optical Long-term Investigations of the Sun telescope at Kitt Peak) offer promise for improvements in statistical and, potentially, physics-based flare forecasts. Work on SEP and flare forecasting will be topics of the subsequent in house work unit.

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APPENDIX

LIST OF ALL PUBLICATIONS DURING TASK PERIOD

(Names of AFRL Task Members are in Bold Face)

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