

Time variations of geomagnetic activity indices Kp and Ap: an update

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Abstract. Kp and Ap indices covering the period 1932 to 1995 are analysed in a fashion similar to that attempted by Bartels for the 1932–1961 epoch to examine the time variations in their characteristics. Modern analysis techniques on the extended data base are used for further insight. The relative frequencies of occurrence of Kp with different magnitudes and the seasonal and solar cycle dependences are seen to be remarkably consistent despite the addition of 35 years of observations. Many of the earlier features seen in the indices and special intervals are shown to be replicated in the present analysis. Time variations in the occurrence of prolonged periods of geomagnetic calm or of enhanced activity are presented and their relation to solar activity highlighted. It is shown that in the declining phase the occurrence frequencies of Kp = 4–5 (consecutively over 4 intervals) can be used as a precursor for the maximum sunspot number to be expected in the next cycle. The semiannual variation in geomagnetic activity is reexamined utilising not only the Ap index but also the occurrence frequencies of Kp index with different magnitudes. Lack of dependence of the amplitude of semiannual variation on sunspot number is emphasised. Singular spectrum analysis of the mean monthly Ap index shows some distinct periodic components. The temporal evolution of ~44 month, ~21 month and ~16 month oscillations are examined and it is postulated that while QBO and the 16 month oscillations could be attributed to solar wind and IMF oscillations with analogous periodicity, the 44 month variation is associated with a similar periodicity in recurrent high speed stream caused by sector boundary passage. It is reconfirmed that there could have been only one epoch around 1940 when solar wind speed could have exhibited a 1.3-year periodicity comparable to that seen during the post-1986 period.

Introduction

Bartels (1963), the initiator of the widely used Kp and Ap indices of geomagnetic activity, attempted a study of the systematic temporal changes in these indices covering the interval 1932–1961. The basic data had just been published as an IAGA Bulletin (Bartels, 1962). In his work he described, in detail, the occurrence characteristics of different magnitudes of the Kp index and their solar cycle dependence as well as placing a special emphasis on the semiannual oscillation of the geomagnetic activity. Since his pioneering work, these indices and other geomagnetic indices such as Aa and Dst (see Mayaud, 1980; Rangarajan, 1989 for details) have also been examined in terms of their cyclic components related to solar activity and other parameters (Delouis and Mayaud, 1975; Gonzalez *et al.*, 1993; and references therein). IAGA Bulletins regularly give statistics on quiet and disturbed intervals and occurrence frequencies of individual magnitudes of Kp index from 0° to 9°. However, as far as we are aware, there has been no effort to update the analysis of Bartels (1963).

When Bartels' work was published in 1963, the first in situ observations from satellites and spacecraft were just beginning to be made. In the next three decades, the solar causes of geomagnetic storms, the distinctive characteristics of geomagnetic activity in different phases of the solar cycle, the role of solar wind velocity, southward component of IMF and the magnetospheric electric fields in the control of geomagnetic activity and the differences in ground signatures in different latitude zones were well studied (see Tsurutani and Gonzalez, 1992; Eselevich and Fainshstein, 1993; Bravo and Rivera, 1994 and Taylor, *et al.* 1994 and references therein).

With the availability of indices for an additional 34 y, it is considered worthwhile to extend Bartels' analysis of Kp indices to cover the entire period 1932–1995 thus providing a summary of information significantly enhancing the content in terms of different levels of geomagnetic

activity. Also, the data base is scrutinized using modern statistical techniques to bring out salient features related to long term and semiannual variations in the occurrence of quiet and disturbed intervals. An exhaustive analysis of the Ap index of geomagnetic activity is also carried out to highlight some unusual periodicities such as ~44 month and ~16 month oscillations (Paularena *et al.*, 1995) and their variations with time.

The 3-hourly Kp indices are first reduced to a coarser scale in the magnitude ranges 0–1, 2–3, 4–5, 6–7, 8–9, 4–9 and 6–9. We follow Bartels' classification of quiet ($K_p = 0-1$) and disturbed ($K_p \geq 4$) intervals to show the transitional character of $K_p = 2-3$. Occurrence frequencies of Kp for each month in each of the categories listed are computed from the data tape available at the World Data Center for Geomagnetism at Kyoto, Japan.

Methods of analysis

The basic data for further analysis are either the occurrence frequencies of Kp index in different magnitude ranges or the daily Ap index. Apart from conventional harmonic analysis of the monthly values which yields amplitudes and phases of the annual and semiannual components, we use also the standard techniques of obtaining spectra through fast Fourier transform (FFT) or the maximum entropy method (MEM). In addition, we adopt the techniques of complex demodulation (Banks, 1975) and singular spectrum analysis (SSA) (Vautard and Ghil, 1989). These two are described in brief.

Complex demodulation is a way of investigating the time local variations of a periodic component in a time series, Xt . The demodulated series at frequency k is given by

$$Yt = Xt \exp(-ikt)$$

It is low-pass filtered to provide the amplitude and phase of the variations in the time series for that particular frequency component. Banks (1975) and Bloomfield (1976) show how the fast Fourier transform routines can be successfully applied to produce the demodulates of the desired central frequencies. It is, however, to be borne in mind that the method yields stable and reliable results only when the underlying process shows slowly varying amplitude and phase (Bloomfield, 1976).

It is well known that the spectrum can only yield the average contribution of a specific oscillation to the total variance and that the phase information is lost in deriving the power density. Vautard and Ghil (1989) describe how a new approach, singular spectrum analysis (SSA), provides quantitative and qualitative details about the deterministic and stochastic parts of a time series. In a further development of the method particularly for use as a tool for short noisy chaotic signal, Vautard *et al.* (1992) generate the reconstructed components (RC) covering the entire data span instead of the principal components (PC) which fall short by the length of the embedding space, as described later.

Among the major advantages of the SSA they list, the following deserve particular mention for the analysis of geophysical time series:

SSA extracts important components of the variability even when the system is non-stationary. The method generates data adaptive filters, whose transfer functions highlight regions where sharp spectral peaks occur and thus helps reconstruction of the original time series with just a few principal components close to the spectral peaks. In contrast to the Fourier components, the PCs need not be sinusoidal in nature. The resolution of spectral peaks in a short noisy time series will be obviously improved if the noise in the series can be substantially eliminated without losing part of the signal as well. SSA does precisely this by decomposing the original time series into its significant signal components with least noise.

The method, in brief, is described next. From the zero-mean time series, autocorrelations are computed for successive lags up to a maximum length M , (termed the embedding space or the viewing window). The autocorrelations are utilised in generating a Toeplitz matrix (with all diagonal elements equal) with the first row given by the sequence of lagged autocorrelations. There are a few different approaches to computing the sample autocorrelations and Vautard *et al.* (1992) recommend using the formula:

$$R(j) = 1/(N-j) \sum_{i=1}^{(N-j)} x_i * x_{i+j} \quad j = 0, 1, 2, \dots, M$$

where N is the length of the time series, M corresponds to the maximum lag and x_i denote the data points with the mean value removed.

Eigenvalues of this matrix are then evaluated in descending order of magnitude together with the corresponding eigenvectors. As the matrix is positive symmetric Toeplitz, all the eigenvalues will be positive. Ideally, the number of non-zero eigenvalues will correspond to the number of independent variables in the system. In the presence of noise in the data, the other eigenvalues will be close to zero defining a noise floor (Sharma *et al.*, 1993). Eigenvectors significantly above the noise level provide the principal components as the projection of the time series along the directions defined by each of the significant eigenvectors. In other words, the eigenvectors serve as data adaptive filters. When quasiperiodic fluctuations are present in the time series, the eigenvectors appear as even/odd pair in phase quadrature, with corresponding eigenvalues nearly equal in magnitude. For oscillations longer than the window size, the even and odd eigenvectors represent an overlapping mean and trend respectively.

As the PCs are filtered versions of the original time series with the M elements of the eigenvectors serving as appropriate filter weights, the resulting series will only be of length $(N - M + 1)$. Vautard *et al.* (1992) have given a method to extract a series of length N corresponding to a given set of eigenelements which they call reconstructed components (RC). The relevant formulae for the k th component are:

Table 1. Frequencies of Kp indices covering the periods 1932–1961 (superscript a from Bartels, 1963), 1962–1995 and 1932–1995 (present analysis)

Kp	Original frequencies			Percentages		
	1932–61 ^a	1962–95	1932–95	1932–61 ^a	1962–95	1932–95
0 and 1	29285	32269	61554	33.89	32.07	32.92
2 and 3	38792	48193	86985	44.90	47.90	46.51
4 and 5	15454	17576	33030	17.89	17.47	17.66
6 and 7	2488	2334	4822	2.88	2.32	2.58
8 and 9	381	236	617	0.44	0.24	0.33
Sum	86400	100608	187008	100.00	100.00	100.00

$$\begin{aligned}
 R(Xi)^k &= (1/j) \sum_{j=1}^M a_{i-j}^k * E_j^k \quad \text{for } 1 \leq i \leq (M - 1) \\
 &= (1/M) \sum_{j=1}^M a_{i-j}^k * E_j^k \quad \text{for } M \leq i \leq (N - M + 1) \\
 &= 1/(N - i + 1) \sum_{j=1}^M a_{i-j}^k * E_j^k \\
 &\quad \text{for } (N - M + 2) < 1 \leq N
 \end{aligned}$$

where E_j^k are the M eigenelements of the k th component

$$\text{and } a_i^k = \sum_{j=1}^M x_{i+j} * E_j^k \quad 1 \leq i \leq (N - M)$$

The percentage of the total variance accounted for by each of the reconstructed components can be computed from the ratio of the individual eigenvalue to the sum of all the M eigenvalues. This percentage then gives an immediate idea of the relative importance of a particular component in the time series.

Results and discussion

Frequency distribution and special intervals

Table 1 gives the frequencies of different magnitude ranges of Kp for the period 1932–95 which are compared with a similar table given by Bartels (1963). As against the 87 664 individual values used by Bartels, our data encompasses 187 008 values. The most significant aspect of this comparison is the fact that the relative percentages of the occurrence of different Kp values have shown an amazing constancy for these two epochs. The deficiency of the Kp index, which is derived only from a predominantly Northern Hemisphere network concentrated in Western Europe and North America, as a truly planetary index has been highlighted earlier (Rangarajan, 1989; Menvielle and Berthelier, 1991). Despite this deficiency, the remarkable consistency of the distribution, over a 64-year period, only goes to show the foresight of Bartels, the care taken in defining the index and the dedicated work of the staff who are associated with the routine scaling from the magnetograms. This table conclusively corroborates the statement of Hapgood (1993) that “though the Ap index is an imperfect representative of global geomagnetic activity, this deficiency does not affect the consistency

of Ap over time”. In respect of homogeneity, it should also be noted that one station in the Southern Hemisphere (Canberra) was added in 1940 and one in the Northern Hemisphere (Lovo) since 1970 (Menvielle and Berthelier, 1991). Apparently these additions have not altered the basic distribution.

Table 2 lists the dates of the 27 quietest days (with Ap = 0) in the years 1932–1995. It is surprising that despite the addition of 26 more years, the number has gone up by only 7 from the list for 1932–69 (Mayaud, 1976). The seasonal distribution is: 17 in the December solstice, (up 7 from Mayaud’s list), 7 in equinoxes and 3 in the June solstice (no change from Mayaud’s list). The most interesting aspect is, of course, the complete absence of magnetospheric quiescence (represented by Ap = 0) between February 1971 and October 1993 and six of the quietest days confined to only the short span of time between Nov. 17 and Dec. 27, 1993. For the 1932–1961 period, Bartels listed 14 days with Ap = 0, all included here. Mayaud (1980, p. 52) showed that when the antipodal Aa index was used to classify days,

Table 2. Days with Ap = 0 in the period 1932–1995

February	17	1933	W
May	28	1934	S
October	19	1934	E
November	22	1934	W
October	6	1935	E
December	23	1935	W
May	24	1936	S
September	16	1936	E
October	27	1936	E
November	13	1936	W
November	16	1937	W
June	23	1938	S
October	12	1954	E
October	12	1955	E
January	6	1963	W
January	9	1963	W
December	10	1963	W
March	28	1964	E
November	10	1965	W
January	16	1966	W
January	8	1971	W
November	17	1993	W
November	20	1993	W
November	23	1993	W
November	24	1993	W
November	27	1993	W
December	27	1993	W

S (northern summer) 3 W (northern winter) 17 E (equinox) 7

Table 3. Duration of at least 32 consecutive intervals of Kp = 0–1 in the period 1932–1995

Year	Start (inclusive)			End (inclusive)			Duration (3h interval)
	Month	Day	UT interval	Month	Day	UT interval	
1932	January	17	7	January	24	2	52 ^b
1932	August	14	5	August	18	5	33
1934	May	13	4	May	17	7	36
1934	October	7	7	October	11	7	33
1934	November	19	3	November	24	5	43 ^a
1935	May	3	6	May	10	4	55 ^b
1935	May	22	4	May	27	3	40 ^a
1935	June	21	7	June	26	8	42 ^a
1935	July	2	6	July	7	7	42 ^a
1936	January	1	2	January	5	2	33
1936	July	20	7	July	24	7	33
1936	September	13	1	September	17	7	39
1936	November	21	6	November	26	5	40 ^a
1936	December	8	2	December	12	2	33
1937	January	22	2	January	26	2	33
1938	July	25	2	July	29	2	33
1938	November	10	4	November	14	4	33
1939	August	1	3	August	5	7	37
1943	June	15	3	June	19	3	33
1944	May	18	1	May	22	6	38
1944	July	23	5	July	28	7	43 ^a
1947	January	8	5	January	15	3	55 ^b
1962	May	20	7	May	26	7	49 ^b
1965	December	13	7	December	18	2	36
1969	July	2	3	July	6	3	33
1970	February	6	2	February	10	5	36
1971	January	6	4	January	10	4	33
1971	November	13	1	November	17	8	40 ^a
1978	January	20	4	January	24	4	33
1993	May	20	7	May	26	7	49 ^b

^a Duration 40 intervals or more^b Duration 48 intervals or more

there is a much larger number of extremely quiet days with an expected distribution of nearly equal number in each solstice and reduced number in equinoxes. Table 2 reinforces Mayaud's (1980) contention that Kp or Ap is not a representative index to classify exceptionally calm intervals of geomagnetic activity.

In addition to this list, we also identified intervals of prolonged quiescence, at least 32 consecutive 3 h intervals of Kp 0 or 1, and these are given in Table 3. These 30 intervals are better distributed with 15 in the June solstice and 13 in the December solstice with only two in the equinox. This leads one to believe that the deficiency in the seasonal distribution of days with Ap = 0 and the conspicuous absence for several years since 1971 could be largely due to (a) improved sensitivity of the magnetometers providing greater resolution and therefore clearer demarcation between K = 0 and K = 1 and (b) the ambient magnetospheric calm periods, associated with slow solar wind velocity and prolonged northward IMF, being still overridden by mild perturbations leading to 2–3 nT change at subauroral latitudes and identifiable on the ground records. Viewed in this sense, the five days in November 1993 and one in December 1993 may, perhaps, be accepted as one of the quietest intervals.

When we consider days associated with intense storms (Ap ≥ 200), given in Table 4, we find only two additional days added to Bartels' earlier list, of which one day, March 13, 1989, has been extensively studied. Once again there is a remarkable gap of more than 25 years. Crooker *et al.* (1992) found that, of the 42 great geomagnetic storms in 1940–1990, 40% occurred in equinoctial months and none in June or December. Taylor *et al.* (1996) find that the occurrence of storms associated with storm sudden commencements (SSC) do

Table 4. 11 days of most intense storms with daily Ap ≥ 200

1941	March 1.....Ap = 207	E
1941	July 5..... 222	S
1941	September 18..... 232	E
1946	March 28..... 213	E
1958	July 8..... 200	S
1959	July 15..... 236	S
1960	April 1..... 241	E
1960	October 6..... 203	E
1960	November 13..... 280	W
1986	February 8..... 202	W
1989	March 13..... 246	E

S (northern summer) 3 W (northern winter) 2 E (equinox) 6

Table 5. Occurrence of $K_p \geq 8$ (for at least 8 intervals in a month) in the period 1932–1995

Year	Month	Frequency
1938	1	8
1940	3	20
1941	9	9
1946	3	15
1946	9	9
1950	8	11
1957	9	25
1959	7	12
1960	4	9
1960	10	11
1960	11	12
1982	9	9
1986	2	8
1989	3	11
1991	6	9

not have a significant seasonal dependence, except when the corresponding Dst value is < -200 nT. Of the 11 events shown in Table 4, six are in equinoxes and three in July. However, the statistics are too meagre to demonstrate that there is a clear seasonal dependence.

The number of instances in a month when $K_p \geq 8$ was reported is summarised in Table 5. It includes only those months when the frequency exceeded eight. Here too one finds the absence of severe activity between 1961 and 1981.

Time series of occurrence frequencies and mean Ap

Time variations of the monthly occurrence frequencies of Kp in different magnitude ranges and that of mean monthly Ap are shown in Fig. 1. The arrangement on

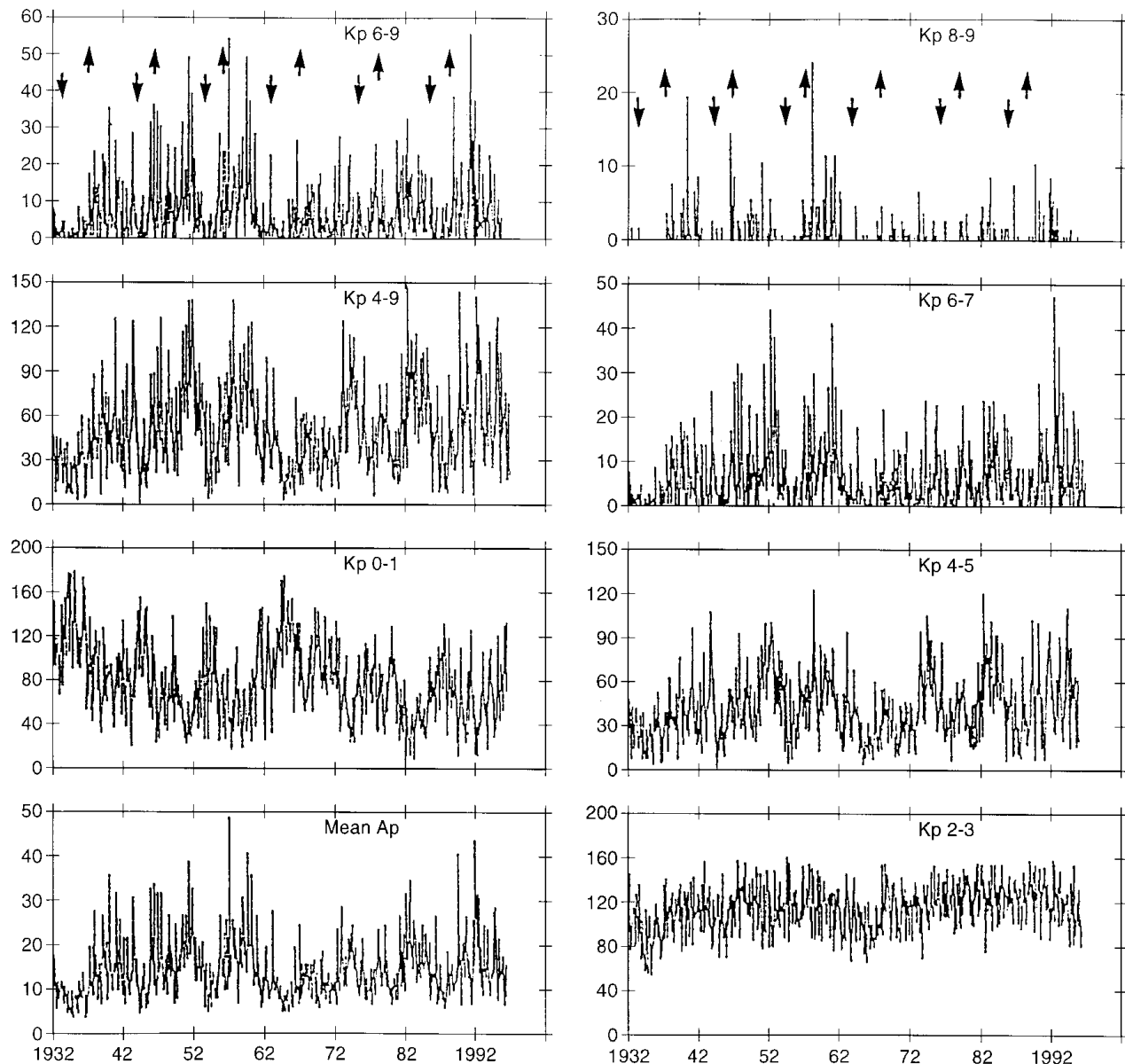


Fig. 1. Monthly mean values of Ap index and occurrence frequencies of Kp index in different categories from 1932 to 1995. Upward arrows indicate solar maximum epoch and downward arrows indicate solar minimum epoch

the left panels of the figure follows Bartels (1963) for immediate comparison. In addition, we also provide, on the right panels, details for the other ranges not covered. In contrast to the presentation of Bartels for each solar cycle separately, these have been graphed for the entire data span. Except for the group $K_p = 2-3$, others are interspersed with some fluctuations but no obvious periodicities are easily discernible by eye. The quiet intervals ($K_p 0-1$) show peak occurrences during solar minimum years with clear maxima in 1934 and 1964 and secondary maxima in 1954, 1976 and 1986. To identify any oscillatory components present in these series, we adopt the method of singular spectrum analysis and derive the spectra of the individual reconstructed components using the maximum entropy method or FFT. Dominant periodicities detected in the series of occurrence frequencies and the percentage variance accounted for by individual components are given in Table 6. Except for $K_p = 2-3$, about 50% of the variability appears to be related to non-periodic random excitations. This percentage appears consistent with the assessment of Gosling (1993) that coronal mass ejections associated with interplanetary shocks and without shocks account for less than 50% of the major or medium storms, and the fact that while shocks are often observed during the maximum phase of the solar activity, high speed wind streams responsible for recurrent geomagnetic activity tend to occur more frequently in the declining phase. The group $K_p = 2-3$ can be considered transitional between quiet and disturbed conditions of geomagnetic activity and only about 20% variability can be associated with some individual components in this case. In all cases, a long-term periodicity of 30 to 35 years, a solar cycle

component and a semiannual variation are distinguishable by their fairly significant contribution.

To complement the frequency distribution of K_p , we also compute the occurrence of quiet and disturbed intervals in three categories using the daily mean A_p index. Monthly occurrence frequencies of A_p with different magnitudes are shown in Fig. 2. Very quiet intervals ($0-1$) appear to be conspicuously absent in the years after 1970 as compared to the beginning of the epoch under scrutiny. However, in general, quiet intervals ($A_p < 5$) seem evenly distributed and show an anticipated inverse correlation with solar activity with more such periods occurring close to solar minimum epochs.

Dependence on the phase of solar cycle

The monthly frequencies are grouped into four categories, according to the phase of the solar cycle, with 15, 12, 18 and 19 total years each for the minimum (min), ascending (asc), maximum (max) and declining (dec) phases respectively. These are shown in Fig. 3. Results of a Fourier analysis of the monthly occurrence frequencies are given in Table 7. The annual and semiannual components are obtained as the first and second harmonics respectively. The following may be noted:

- A clear difference in the phase of the semiannual component (SAV) between minimum and maximum solar activity periods for the first three K_p groups shown.
- A large amplitude SAV during periods of enhanced geomagnetic activity (K_p groups 4-5, 4-9, 6-7 and 6-9) in the declining part of the solar cycle.

Table 6. Dominant periodicities identified from fast Fourier transform and singular spectrum analysis of the time series of occurrence frequencies. Percentage variance accounted by individual components of the singular spectrum are indicated

Kp category	Period	Amplitude (from FFT)	Period	Variance (%) (from SSA)	Cumulative percentage
0-1	341 month	17.4	440 month	18	18
	128	9	120	19	37
	43	11	60	6	43
	21	5	44	2	45
	12	5	15.4	2	47
	6	10	12.5	2	49
				6	8
2-3	512	7	440	6	6
	12	5	110	4	10
	6	4	12	5	15
			6	2	17
4-5	341	9	440	9	9
	93	9	120	17	26
	64	7	82	5	31
	16	4	63	4	35
	6	8	16.4	5	40
			6	9	49
4-9	341	11	440	7	7
	102	11	120	17	24
	64	8	82	5	29
	17	5	63	4	33
	6	12	16.4	4	37
			6	11	48

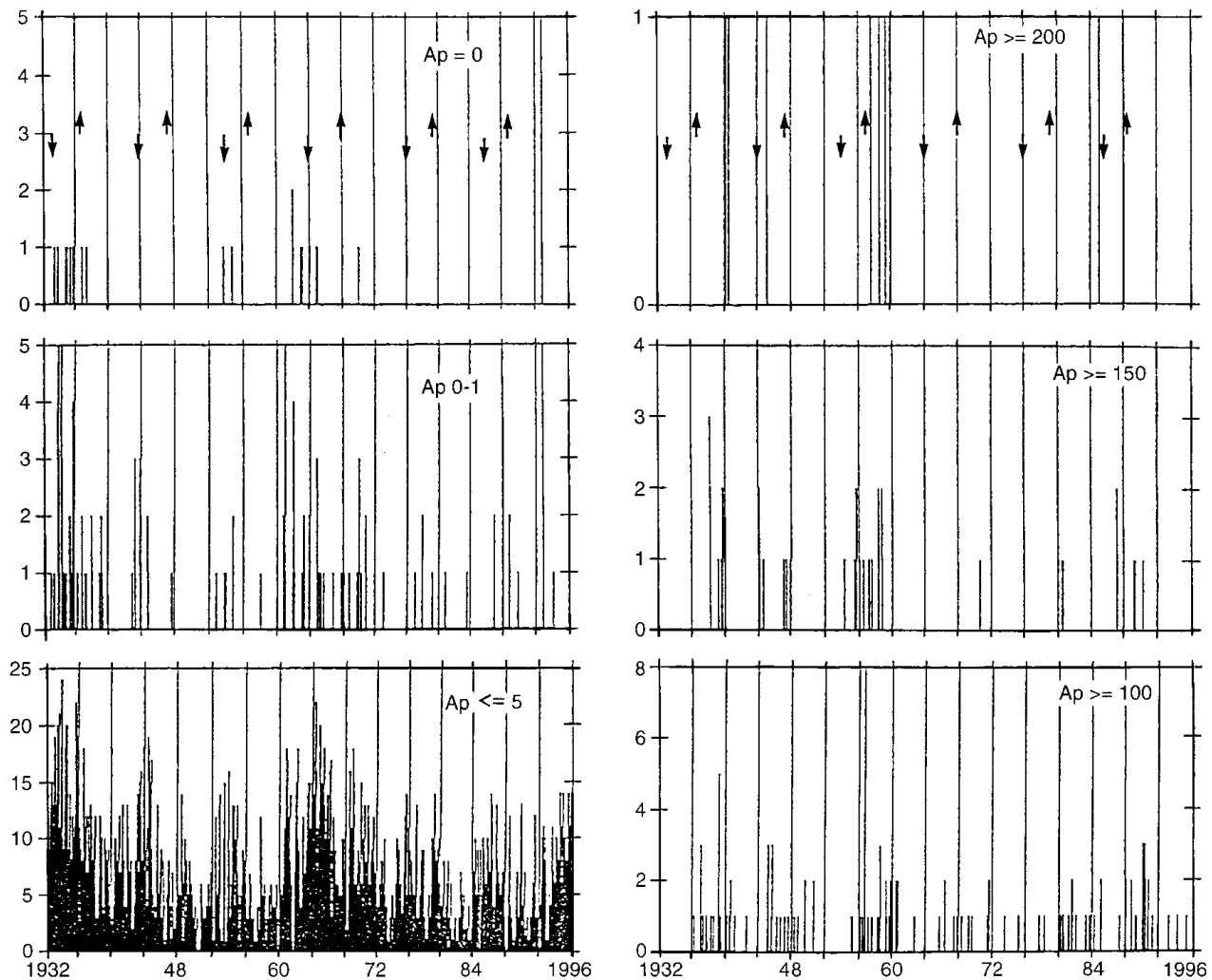


Fig. 2. Occurrence frequencies of Ap index, for each month, in different magnitude ranges from 1932 to 1995. *Left panels* correspond to quiet intervals and *right panels* to most disturbed intervals. *Upward*

arrows indicate solar maximum epoch and *downward arrows* indicate solar minimum epoch

c. The smallest amplitudes of both SAV and annual variation (AV) during the ascending part of the solar cycle for all the groups. However, for the highest activity groups (Kp = 6–7 and 6–9), the annual component is not found to be the smallest during the ascending phase.

Following Bartels (1963), we also give in Table 7 the ratio(s) derived from the departure of the semiannual component (C2) from the mean value (m) of frequencies at the crest and trough of the wave. This ratio varies between 1.2 and 3.1. In general, the ratios for minimum epochs are greater in magnitude and in spite of the smaller frequencies for $Kp \geq 6$, the preponderance in equinoxes is clearly manifested (ratio ~ 3.0). A similar feature was recently shown to be present for SSCs with associated $Dst < -200$ nT by Taylor *et al.* (1996).

The results obtained from this extended data base continue to replicate the initial results of Bartels (1963, see his Fig. 6) with insignificant SAV for $Kp = 4-9$ during the ascending phase and large amplitudes in association with $Kp = 0-1$ during the solar minima.

This reinforces the earlier conclusion about the strong consistency in the time variations of the Kp and Ap indices for more than 6 solar cycles.

As the data base since Bartels' (1963) efforts has more than doubled now, and as more modern analysis techniques have become available, we extend the scope of our analysis of the Kp and Ap indices for better insight into the long- and short-term variabilities, as described later.

Time variations in the sequence of quiet and disturbed intervals

Occurrence frequencies of groups of Kp indices representing quiet and disturbed conditions are computed restricting the data first to the three Lloyd's seasons, corresponding to Northern Hemisphere summer (May to August), equinox (March, April, September and October) and winter (November to February) and to consecutive occurrence over 4, 6 or 8 three-hourly intervals.

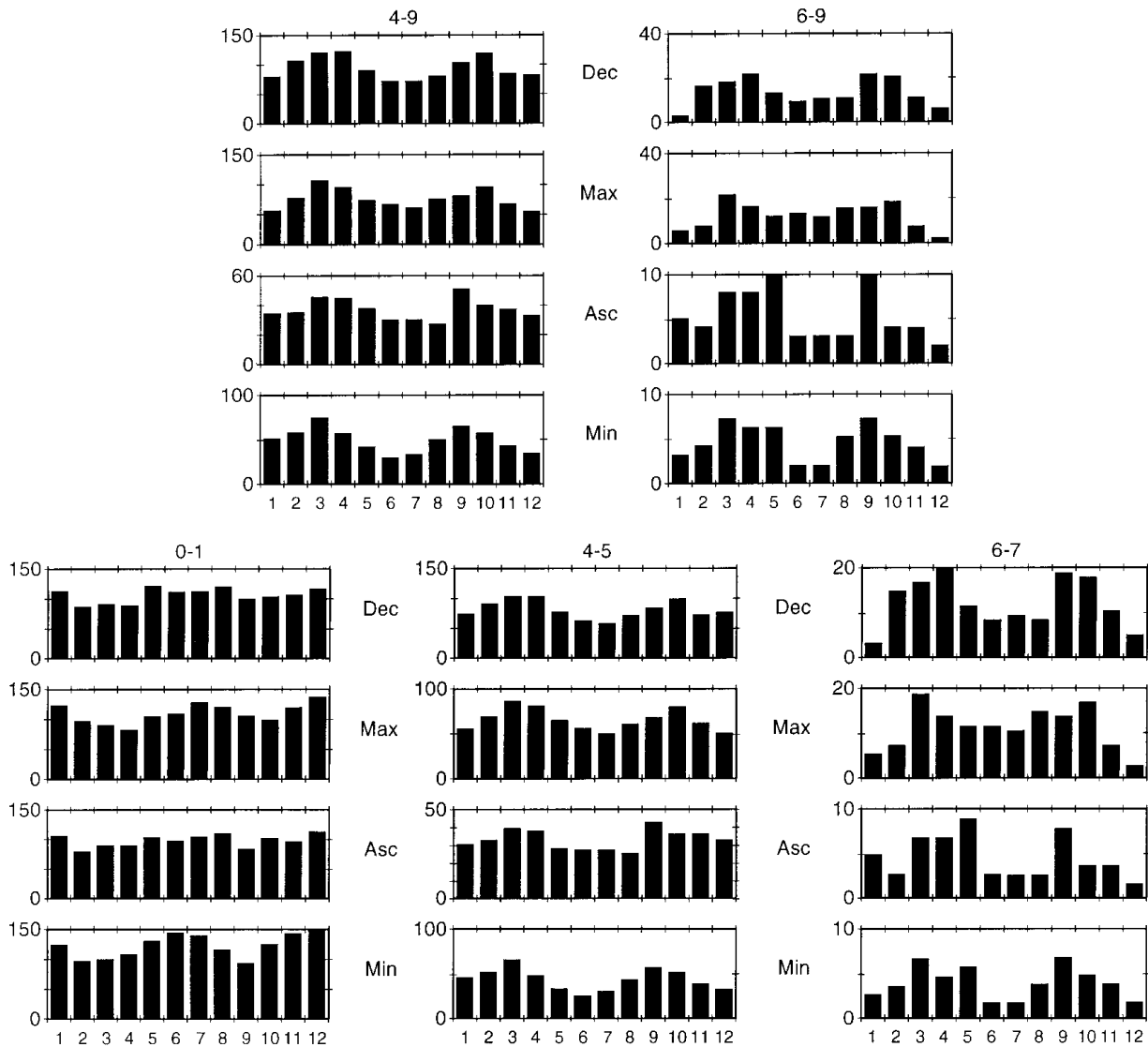


Fig. 3. Mean monthly occurrence frequencies of Kp index in different magnitude ranges as a function of the phase of the solar cycle: minimum (*Min*); ascending (*Asc*); maximum (*Max*); and declining (*Dec*)

Figure 4a, b depicts the occurrence frequencies for the three seasons and for the complete year. For quiet intervals ($K_p = 0-1$, Fig. 4a), the years 1933–1936 and 1965–66 were the most favourable, irrespective of the number of consecutive intervals considered. This tendency can be seen even when the data are seasonally subdivided. Interestingly, there is no single year in any of the 12 plots when the occurrence of $K_p = 0-1$ is zero. Thus we can always identify 24 hours of magnetospheric calm periods in each season to use for statistical analysis.

In contrast, the yearly occurrence of disturbed intervals of different lengths, shown in Fig. 4b, has several blanks (in particular, for length 8). This is consistent with the fact that severe geomagnetic disturbances, with $K_p \geq 6$, will tend to recover in time scales shorter than 24 hours and that even moderate geomagnetic storms (with K_p 4 or 5) do not sustain geomagnetic activity at that level for that long, as substorms are

considered to be bursty phenomena. If we confine our search to lengths less than 24 h, we can once again find sufficient samples, although there are still occasional data gaps as in 1934–35 for length 6. No significant correlation with the solar cycle is seen.

Relationship with solar activity

To ascertain the relation between solar activity and the occurrence frequencies, we computed lagged correlations between the annual mean sunspot number (R_z) and the frequencies for each category. These are depicted in Fig. 5. Positive lags ($+k$) in the diagram correspond to the coefficients obtained while correlating the current years' occurrence frequencies with R_z 'k' years later; in other words, shifting the R_z curve backwards by k years in time relative to the occurrence frequencies. It may be noted that in each category of

Table 7. Amplitudes and phases derived from harmonic analysis of the monthly occurrence frequencies of Kp in different phases of the solar cycle and the ratio of the frequencies at the maximum and minimum epochs

Kp category	Solar cycle phase	Mean frequency (m)	Annual component		Semiannual component		$s = (m + c2)/(m - c2)$
			Amplitude	Phase	Amplitude (c2)	Phase	
0–1	Minimum	120.7	6.7	201.9	24.6	158.1	1.51
	Maximum	106.2	9.5	177.3	15.9	117.6	1.35
	Ascending	96.6	3.5	211.9	8.1	138.7	1.18
	Declining	103.8	7.6	227.0	9.7	140.6	1.21
4–5	Minimum	44.7	6.3	83.4	14.4	330.6	1.95
	Maximum	66.3	5.0	30.7	14.7	299.4	1.57
	Ascending	33.2	2.6	121.6	5.5	291.4	1.40
	Declining	81.8	9.6	63.9	15.4	298.5	1.46
4–9	Minimum	49.0	6.2	78.3	16.4	327.5	2.01
	Maximum	79.7	5.6	347.7	19.8	303.6	1.66
	Ascending	38.5	1.8	82.9	8.0	292.2	1.52
	Declining	95.5	9.0	53.8	22.8	299.2	1.63
6–7	Minimum	4.3	0.3	0.0	2.2	302.2	3.10
	Maximum	11.7	3.0	286.8	4.5	309.5	2.25
	Ascending	4.8	1.2	345.0	2.0	282.7	2.43
	Declining	12.5	1.2	319.0	6.5	299.3	3.17
6–9	Minimum	4.4	0.4	338.8	2.3	304.1	3.19
	Maximum	13.5	3.6	285.4	5.6	310.3	2.42
	Ascending	5.3	1.4	346.7	2.5	290.4	2.79
	Declining	13.8	1.2	292.8	7.4	300.6	3.31

Kp, there are two panels corresponding to two different lengths of consecutive intervals.

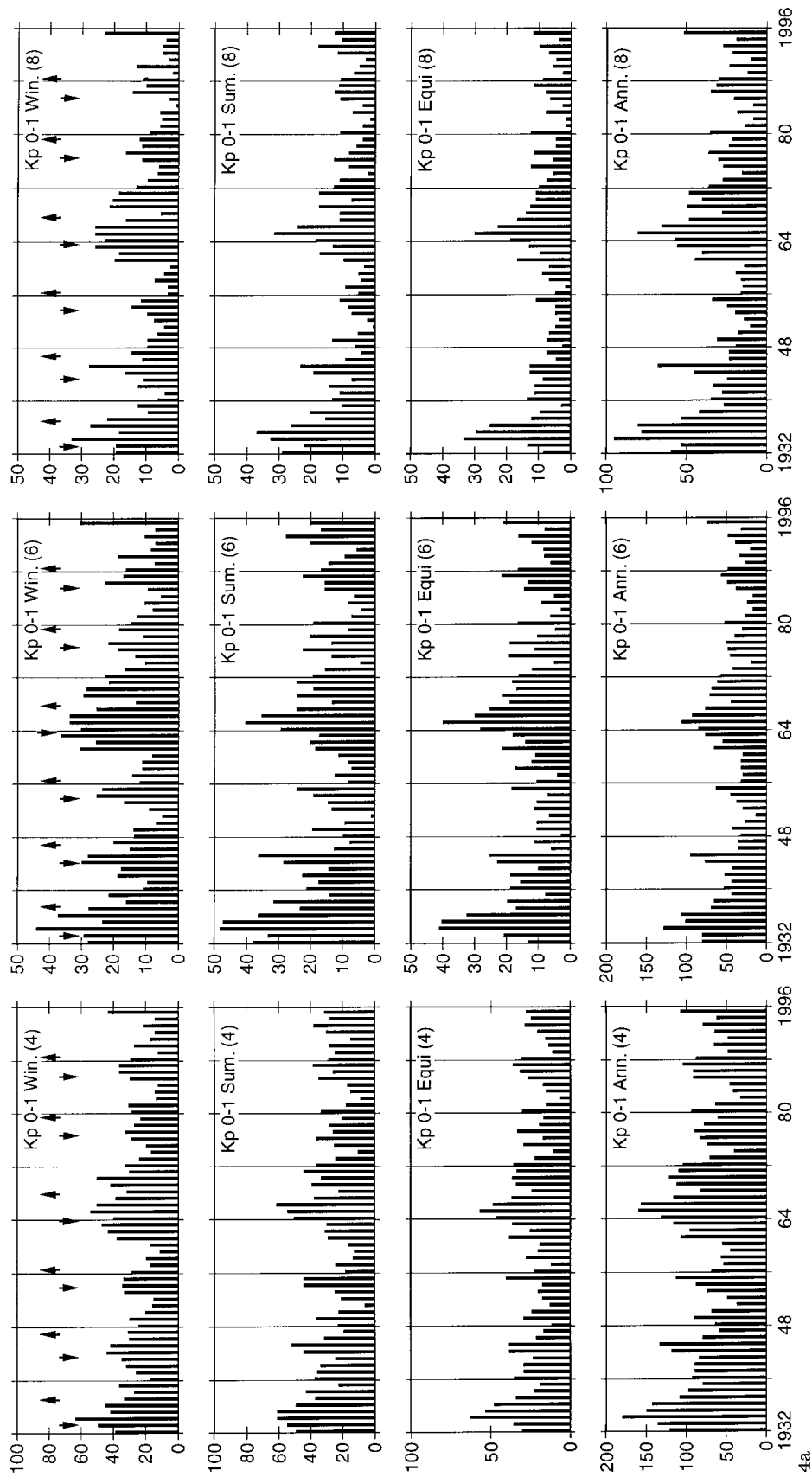
Feynman (1982) suggested that geomagnetic activity, as represented by the Aa index, can be divided into two components: (1) linearly related to solar activity and (2) a residual part with largest values before the solar minimum epochs. For sequences of $Kp \geq 6$ (at least four consecutive ones), the correlation peaks at 0 lag and the peaks are spaced 10–11 years apart indicative of the direct connection between solar and severe activity. This implies, in turn, that solar transients like flares and CMEs, occurring most frequently during solar maximum epochs, generate severe geomagnetic disturbances. As SSCs are known to be directly related to solar activity, geomagnetic activity associated with coronal mass ejections and interplanetary shocks will peak during solar maximum years (Gosling, 1993). However, the moderate magnitudes of the correlation coefficient for this category and the one for $Kp = 6-7$ (4) is indicative of the fact that such sequences of disturbances are not confined to solar maximum only but are also possible during other phases of the solar cycle.

The most significant correlations are associated with the sequence of occurrence of $Kp = 4-5$ (both 4 and 8 consecutive intervals). This level of geomagnetic activity is generally associated with moderate magnetic disturbances, often recurrent in nature. Recurrent geomagnetic activity is more frequent during the declining phase of the solar cycle (Sargent, 1985) and this is commonly associated with high-speed solar wind streams emanating from coronal holes, corotating with the sun (Legrand and Simon, 1989). The corresponding correlations with solar activity will, therefore, lag the peak solar activity by a few years. On the other hand, Ohl (1971)

discovered that the level of geomagnetic activity in the declining phase of a solar cycle is related to the magnitude of the maximum solar activity in the ensuing cycle (see Wilson, 1990 for further references) and showed that it could serve as a useful predictor for the amplitude of the coming solar cycle. Such a relationship between geomagnetic activity in the previous years close to solar minimum and the maximum R_z for the current cycle was reconfirmed by Nevanlinna and Kataja (1993) for solar cycles 9 to 22 covering the period 1844 to 1990.

Sargent's (1985) recurrence index, based on half daily values of aa for each solar rotation, emphasised more the persistence in the form of the geomagnetic activity changes and less on the level of geomagnetic activity. The lagged correlations, plotted on Fig. 5, on the other hand, highlight the relation between solar activity and geomagnetic activity at different levels and durations. To our knowledge, such a relationship has never been presented before. The peak at a lag of +7 years is consistent with the observations of Ohl (1971) regarding the relation between the geomagnetic activity in the declining phase and the solar maximum magnitude in the next cycle, as there is a gap of approximately seven years between the years before minimum and the next maximum. It thus appears that the frequencies of $Kp = 4-5$ in the years prior to solar minimum could also be a predictor tool for the maximum in solar activity of the next cycle.

The occurrence of sequences of quiet intervals [$Kp = 0-1$ (4) or $0-1$ (8)] demonstrates the anticipated anti-correlation with solar activity with maximum negative value for a lag of -1. In all the categories, the solar cycle dependence is again evident with peak separations of 10 to 11 years.



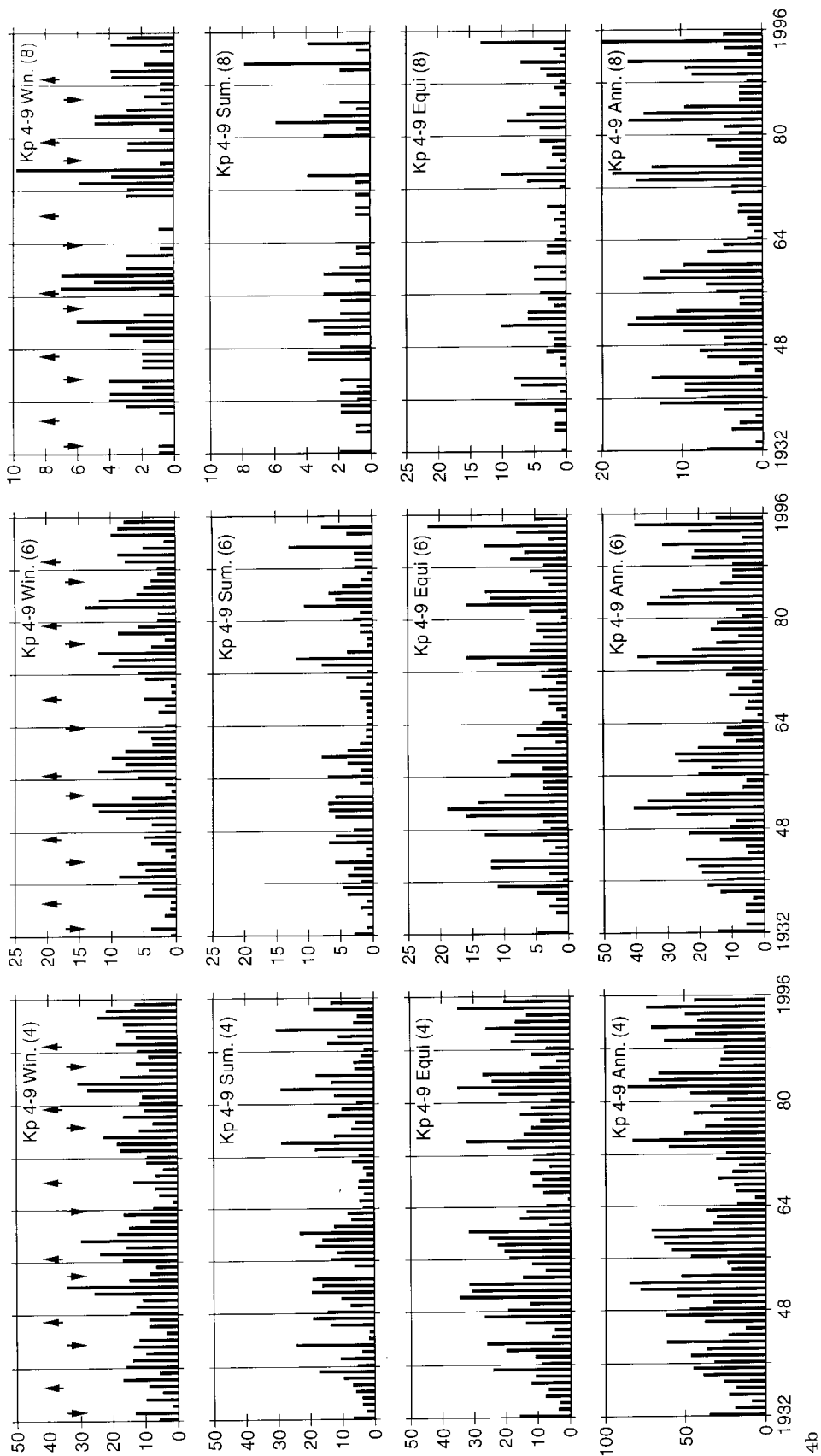


Fig. 4 a Monthly occurrence frequencies of $K_p = 0-1$ (quiet intervals) as a function of 3 Lloyd's seasons corresponding to December solstice (*Win.*), June solstice (*Sum.*) and equinoxes (*Equi.*). The frequencies are derived for three different specifications: consecutive occurrence over 4 intervals (*left*), 6 intervals (*centre*) and 8 intervals (*right*). Upward arrows indicate solar maximum epoch and downward arrows indicate solar minimum epochs; **b** Same as **a** but for the disturbed intervals with $K_p \geq 4$

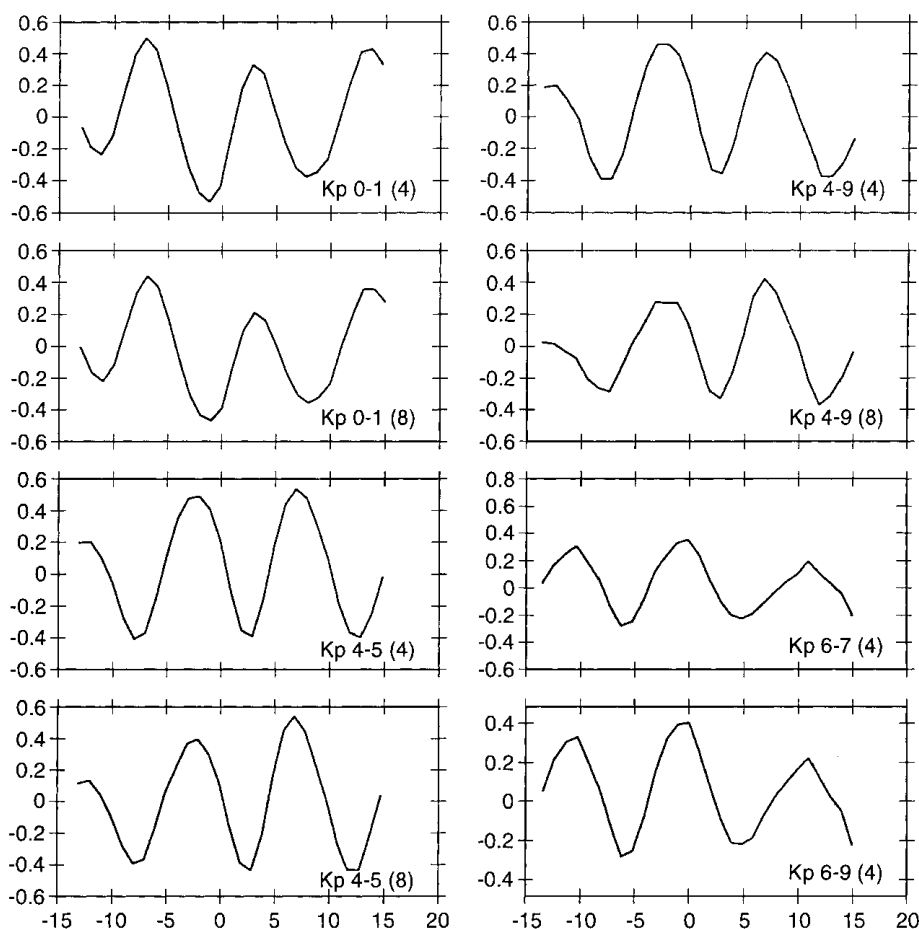


Fig. 5. Lagged correlations between annual mean sunspot number and the occurrence frequencies of Kp in different categories and lengths of consecutive intervals with same magnitude. Positive lag (in years) corresponds to the correlation between current annual values of Kp and annual Rz years later

Semiannual variation (SAV) in Kp and Ap

That there is an enhancement of geomagnetic activity in the equinoctial months has been quite well known for a long time (Chapman and Bartels, 1940, and references therein for earlier work) but the theories and models to account for the enhancement have yet to be reconciled. The “axial hypothesis” (Cortie, 1912; Priestler and Cattani, 1962) relates it to the heliographic latitude excursion of the earth between $+7.2^\circ$ and -7.2° , with predicted maxima on September 6 and March 5. The “equinoctial hypothesis” (McIntosh, 1959; Boller and Stolov, 1970) is based on the effectiveness of solar wind-magnetosphere interaction dependent on the angle between the Earth’s dipole axis relative to the Sun-Earth line. The predicted dates of maxima turn out to be September 23 and March 21. Russell and McPherron (1973) suggested that the semiannual enhancement is brought about by two separate annual components, one with a maximum on April 5 and the other on October 5. The R-M model considers the fact that the IMF is ordered in the solar-equatorial coordinate system while the solar wind-magnetosphere interaction is ordered in the solar-magnetosphere coordinate system (see Russell, 1971 for coordinates). Murayama (1974) concluded that the SAV in Kp can be interpreted as the combined effect of the R-M mechanism and the heliographic latitude dependence of the solar wind parameters. Berthelier

(1976), on the other hand, adduced both the R-M and equinoctial hypotheses as plausible mechanisms for the SAV observed in the Am index.

To examine the amplitude and phase of the SAV in the Aa and Ap indices, Green (1984) adopted the technique of complex demodulation. Green (1984) obtained the demodulates of the SAV in both the Aa and Ap indices and observed a complex 11-year modulation in the SAV amplitude of the Aa index. Between 1938 and 1966 there was enhancement in the SAV amplitude without any associated 11-year variation. Ap index showed marked similarity in its behaviour to Aa during the interval 1932–1980.

We carried out complex demodulation on the monthly frequencies of Kp in different categories, and also on the monthly mean Ap for the period 1932–1995. The first and last 10% of the data series are modified in the process of obtaining demodulates through FFT due to the use of a cosine bell taper to avoid spectral leakage (Bloomfield, 1976). The changes in the amplitude and phase of the SAV in the different time series are shown in Fig. 6. For Ap, they reproduce Green’s results and extend them beyond 1980 by 15 years.

The profiles of amplitudes and phases for different ranges of Kp index corresponding to moderate ($K_p = 4-5$) or severe disturbances ($K_p \geq 6$) or disturbances in general ($K_p \geq 4$) are all parallel to that of Ap with largest amplitudes between 1940 and 1950 and least

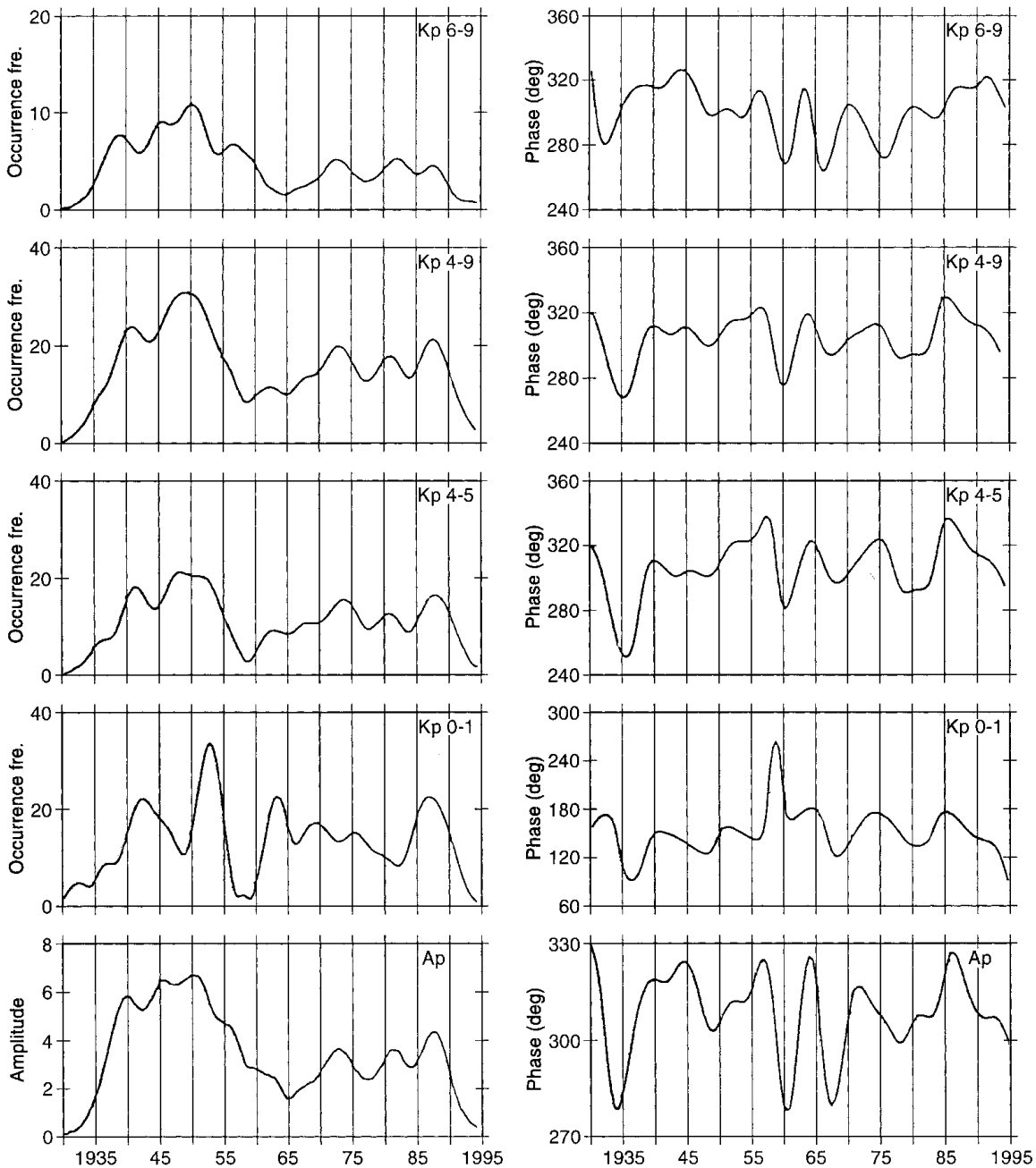


Fig. 6. Time local changes in the amplitude and phase of the semiannual component in Ap and occurrence frequencies of different categories of Kp, derived from complex demodulation of the

corresponding time series shown in Fig. 1. Note that the first and the last few values will not be 'correct' due to the procedure adopted in tapering the time series prior to FFT

during 1965. The absence of any maximum close to 1957, the year of largest annual mean Rz indicates an apparent lack of solar cycle dependence. The demodulate phases for all groups (except Kp = 0-1) and Ap are centred around 300° (corresponding to the last weeks of March and September). We shall not comment on whether it is close to the predicted dates of one of the three mechanisms as the difference between the three dates is comparable to the variability in phase angles noticed here.

The occurrence of quiet intervals (Kp = 0-1) also has a semiannual component associated with it but the

time variation of its amplitude does not track that of Ap or the other groups of Kp considered. The largest SAV in quiescent conditions is seen over the restricted period of 1953-54. A striking feature of the amplitude demodulates of SAV in Fig. 6 is the prominent minimum close to the 1957 solar maximum for the occurrence frequencies of Kp = 0-1, 4-5 and 4-9 and its shift to coincide (except for Kp = 0-1) with the 1965 solar minimum for the Ap index. Again, except for Kp = 0-1, two different levels of amplitudes are maintained on either side of this minimum (ignoring first and last few years as mentioned earlier). In the analysis of aa indices in terms of two

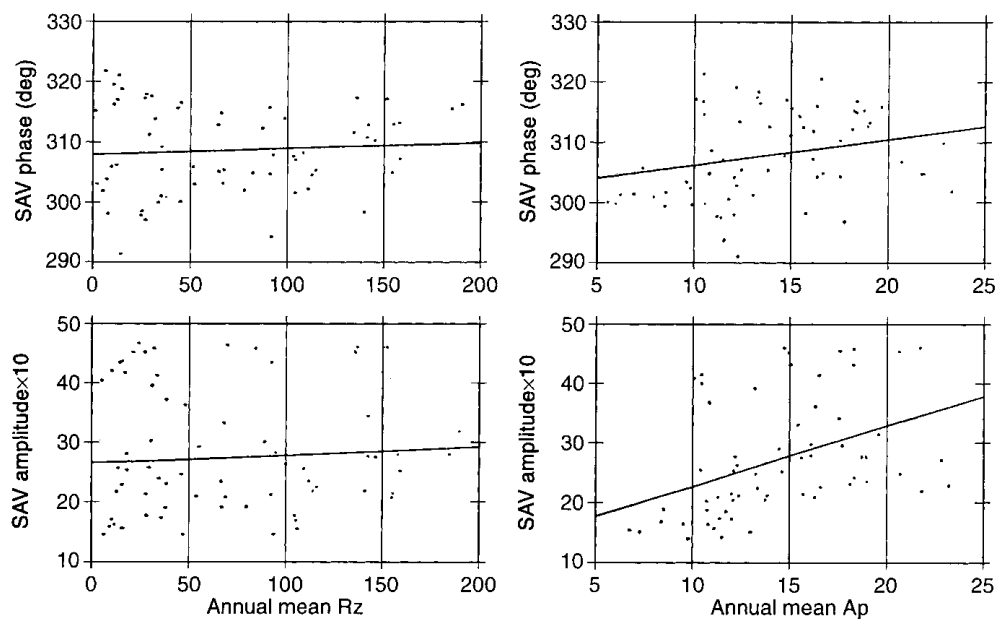


Fig. 7. Scatter plots and best fit straight lines of the amplitude and phase of SAV (for each year) and the corresponding annual mean sunspot number (*left*) or the corresponding annual mean value of Ap index (*right*)

components, $\langle aa \rangle R$, directly related to sunspots and $\langle aa \rangle i$, the residual part, Feynman (1982) found a prominent transition in the time variations of both the parameters close to 1960 with the appearance of oscillations of very diminished amplitude. This was interpreted as a part of a long cycle in geomagnetic activity with a periodicity of nearly 60 y. Gorney (1990) suggested that the overall envelope of geomagnetic activity is well correlated with solar wind velocity while individual events may be triggered or modulated by the interplanetary magnetic field. Since SAV is at least partly due to the R-M mechanism and thus dependent on the IMF orientation, the observed minimum in the SAV demodulates may be related to corresponding features in the monthly averages of solar wind velocity. Bz is expected to average out to zero over such time scales. Gazis *et al.* (1995) attribute the variations in solar wind velocity on different time scales to different physical processes and suggest that solar wind source regions undergo long term variations causing the changes in velocity observed in the course of a solar cycle. These inferences, too, should then imply a minimum value for the epoch 1958–1965. Interestingly, moderate geomagnetic disturbances ($K_p = 4-5$) and quiet levels have associated SAV minima near solar maxima while severe disturbances ($K_p = 6-9$) and the mean level of activity indicated by Ap have their minima during solar minima. This, too, is consistent with the solar cycle patterns of CMEs, solar transients, recurrent streams and slow steady streams.

Murayama (1974) found that the SAV amplitude and phase exhibited a systematic variation with sunspot number. The amplitude diminished from 2.88 to 1.10 for an Rz change from 7 to 100 followed by an increase to 1.90 for Rz \sim 165. The phase change was less pronounced. Adopting the same procedure for Aa, grouping the years into ten bins with increasing sunspot number, Green (1984) contradicted Murayama's results.

An average amplitude of 1.91 and phase of -137.4° for the SAV did not show any dependence on Rz. Green (1984), however, found a non-linear (parabolic) enhancement of the SAV amplitude with the magnitude of the index Aa. Once again the phase angles remained fairly constant with an average close to the dates predicted by the equinoctial hypothesis.

In Fig. 7, we plot the SAV amplitude and phase as a function of the annual sunspot number and the magnitude of the Ap index. To highlight the scatter in phase, we use the individual yearly mean values instead of averaging over wider bins. It is immediately apparent that there is no solar activity dependence of SAV amplitude or phase (correlation coefficients 0.087 and 0.075 respectively). This correlation is considerably poorer than the value of 0.59 between Rz and SAV in Aa index given by Green (1984). One possible reason for the improved correlations obtained by Green (1984) is the process of dividing Rz and Aa into just 10 groups. It is also relevant to note that the relationship between the 3-hourly indices ap and am is approximately parabolic whatever the time interval and that between 3-hourly index aa and am is strictly linear (Mayaud, 1980, p. 84). The longer time span used for Ap in the present analysis makes the comparison with the results for the Aa index of Green (1984) more meaningful and the differences in detail fairly reliable. The mean phase angle 308.3° yields a date of March 26, close to the epoch predicted by the equinoctial hypothesis. The associated standard error can lead to an uncertainty of about 7–8 days (15°) still far removed from either of the April 5 or March 5 dates predicted by R-M and the axial hypotheses. In contrast, the SAV amplitude, and to some extent the phase, shows a small measure of dependence on the level of geomagnetic activity with a correlation coefficient of 0.417 for amplitude and 0.24 for phase.

Using daily Ap data and an appropriate superposed epoch analysis, Gonzalez *et al.* (1993) find three separate

peaks in activity corresponding to March 12, April 1 and April 10, close enough to the three dates predicted by axial, equinoctial and R-M models. Their results indicated a multiple origin of the SAV leading them to conclude that it is unrealistic to search for a single cause for this well-known seasonal variation. Our Fig. 7 also appears to emphasize this conclusion.

Spectral components of Ap through singular spectral analysis

The index Ap of geomagnetic activity has been analysed earlier for the identification of significant cyclic components by Fraser-Smith (1972), Kane (1986), Gonzalez *et al.* (1993) and others. Usually the fast Fourier transform (FFT) routine, the cosine transformation of the auto correlations (popularly known as the Blackman-Tukey approach) or the maximum entropy method (MEM) (Childers, 1978) have been utilised to identify frequencies associated with significant spectral peaks. Gonzalez *et al.* (1993) carried out an exhaustive spectral analysis of Ap covering the period 1932–1982 to highlight some significant new results such as the presence of a ~ 4 -year periodicity, variability in the signature of the solar rotation periodicity and the nature of the semiannual variation.

Recently, Rangarajan and Araki (1997) have applied the methodology of singular spectrum analysis (SSA) to the equatorial Dst index to elucidate successfully multiple time scales in its fluctuations. Here, SSA is similarly used to isolate significant spectral components in the time series of mean monthly Ap values from 1932 to 1995. The first 12 components above the noise floor account for about 60% of the total variance in the time series of Ap, indicating that the balance is contributed by random processes or non-stationary quasi-periodic causes. We combine appropriate components based on the phase quadrature of the eigenvector pairs. The time-variations of the reconstructed components in decreasing order of their relative contribution to the total variance in Ap are shown in Fig. 8 (a–i).

These individual time series are then subjected to maximum entropy spectral analysis to identify precise periodicities. SSA ensures that there will be only one or two dominant frequency components in each individual reconstructed component. These are respectively (a) 375 month (15); (b) 110 month (11); (c) 6 month (17); (d) 43.5 month (3.3); (e) 15.7 month (5); (f) 21 month (3); (g) 13.7 month (1.7); (h) 30.6 month (4); and (i) 12 month (1.3). The numbers in parentheses give the relative percentage contribution to the total variance of the original time series. Of these, the semiannual, 15.7 month, quasibiennial oscillation (QBO ~ 21 month) and 30.6 month variations are associated with eigen pairs and hence can be considered sinusoidal. In contrast to other methods, the greatest advantage of the SSA approach is the possibility to visually see the time-local properties of the individual components. We next discuss the features of each component in the light of earlier results and point out some new and significant results.

Approximately 30 year component

Figure 8a depicts the nature of the ~ 30 -year oscillation (375 month) in the Ap index. Rotonova *et al.* (1985) identified this periodicity in geomagnetic field components while Gonzalez *et al.* (1993) placed the spectral peak in the Ap index at around 32–33 y and Delouis and Mayaud (1975) found a peak at 36.0 y in the aa index. In these spectra, these periodicities appear at the low frequency end and have, therefore, larger uncertainties associated with them. We assert, following Vautard *et al.* (1992) that quasi-periodicities detected after singular value decomposition should be much closer to the true periods of oscillations. As with the complex demodulates for SAV, the epoch near 1964 was indicative of a sharp transition even for this longer period oscillation. This periodicity is overlain by a quasi-persistent solar cycle component of relatively small amplitude.

Solar cycle component

In Fig. 8b, the time profile of the likely solar cycle component is shown. The periodicity of 110 month, however, makes its association with solar activity uncertain, however, the signal is unambiguously seen in most of the years and with an amplitude of 2–3 Ap units (4–6 nT). Borello-Filisetti *et al.* (1992), examining the connection between solar activity and the level of geomagnetic activity, found a real decrease in the correlation between the two parameters in the current century. They suggested that the observed variability in geomagnetic activity is due to solar wind emanating from polar coronal holes. Legrand and Simon (1989) also propose four different causative sources for geomagnetic activity (1) quiet levels associated with ambient solar wind; (2) recurrent disturbances due to high speed streams; (3) SSC storms generated by shock events; and (4) fluctuating activity which is distributed irregularly during a 5–6 y interval in each solar cycle, called the solar multipole phase. Though each may have a near 11-y quasi-periodic variation, the net effect could well lead to the observed ~ 110 month periodicity in Ap. It will be useful to analyse individual solar wind parameters for detection of commensurate periodicities. This is being taken up separately. Other possibilities for the absence of a periodicity close to 11 y could be that geomagnetic activity in the declining phase, recurring after 27 days, shows a difference between even and odd cycles (Hapgood, 1993) and that the length of solar activity cycle itself has a variability between 9 and 12 y with the spectral peak in Rz nominally at 10.2 y. A large variability of amplitude from cycle to cycle appears as the dominant feature in this frequency range.

Six month cycle

Figure 8c depicts the amplitude changes in the semiannual variation in Ap. This figure complements Fig. 6. The demodulate amplitudes are, in general, the upper

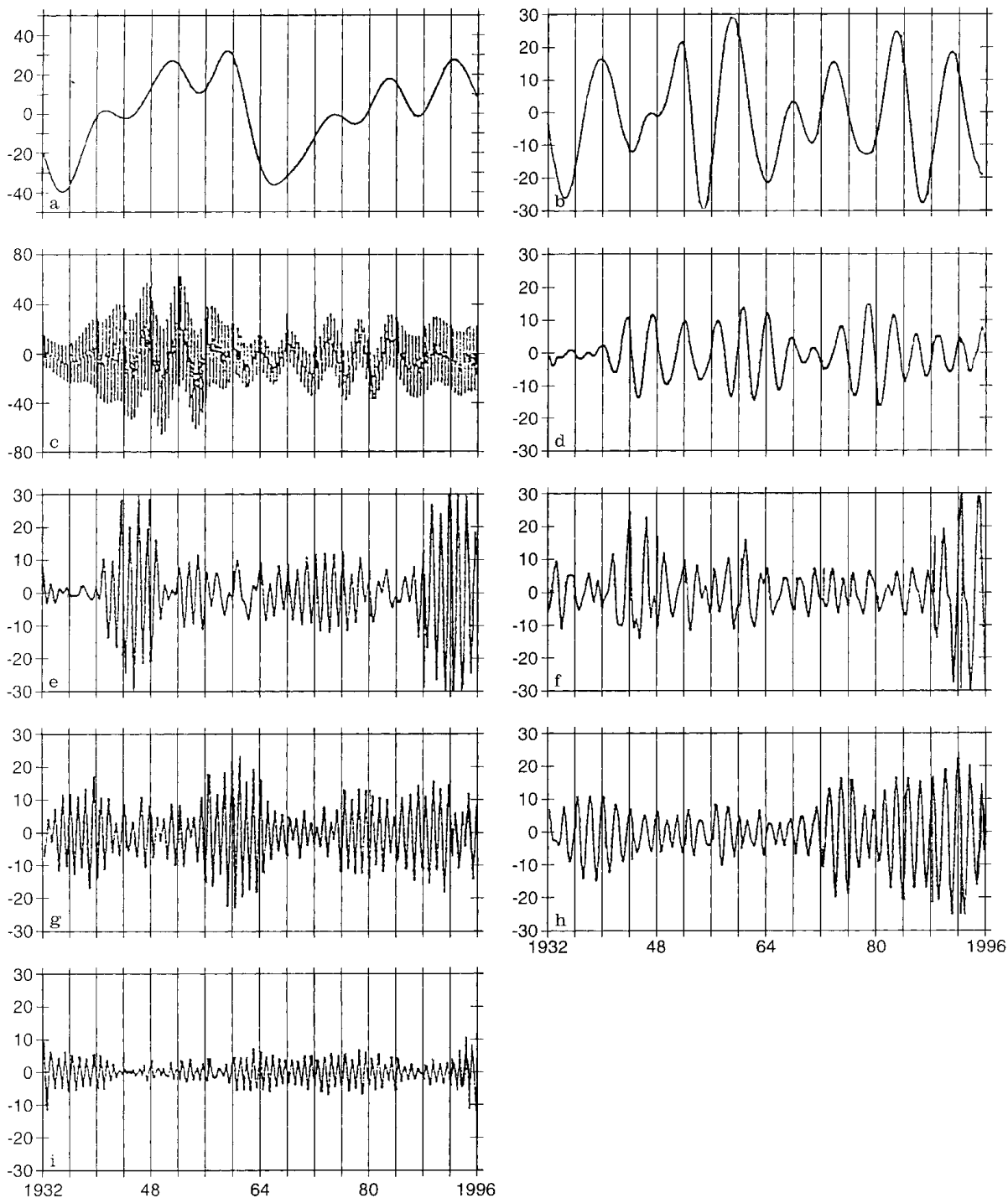


Fig. 8a-i. Reconstructed components of significant oscillations in the time series of monthly mean Ap index, derived from the singular spectrum analysis. Approximate periodicities and the percentage variance accounted by the oscillations are:

a 375 month (15%); **b** 110 month (11%); **c** 6 month (17%); **d** 43 month (3.3%); **e** 15.7 month (5.1%); **f** 20.6 month (3%); **g** 13.1 month (1.7%); **h** 30.6 month (4%); **i** 12 month (1.3%). Note that the amplitudes are magnified by a factor of 10 units

envelope of the curve. They are, however, obtained from a band of frequencies centred on the 6-month spectral peak and hence, will not have a one-to-one correspondence with the amplitude profile shown here. The actual time variation presented in Fig. 8c brings out better some interesting features like the modulation of the SAV amplitude with a periodicity of 4–5 y which is very

prominently seen between 1944 and 1988, the absence of solar cycle modulation and the enhancement of amplitudes between 1940 and 1956.

It is worthwhile once again to stress how effective SSA is to emphasise features otherwise hidden in a noisy time series. Bartels (1963) had, indeed, examined the variability in SAV for individual years (see his Fig. 10)

to show that the solar minimum year 1954 stands out with a large magnitude for SAV whereas the 1958–1961 era exhibited the SAV “particularly badly”. He attributed this to the masking of the SAV by solar events in solstices.

According to Orlando *et al.* (1993), several mechanisms may be simultaneously operative but their relative importance remained to be quantified. From their analysis of Aa indices for different phases of the solar cycle, Orlando *et al.* (1993) inferred that recurrent high speed streams in the declining part of the solar cycle results in a semiannual variation with stable phase. For the period 1965 to 1987, southward IMF (Bs) or better still $B_s V^2$ correlates well with monthly Aa index. They concluded that Bs control of the SAV supports the R-M hypothesis whereas the part of the SAV associated with solar wind velocity variations support the ‘axial’ hypothesis.

Approximately 43 month cycle

In Fig. 8d, we look at the time profile of a quasiperiodic 43 month oscillation. Except for brief periods between 1932 and 1940 and 1968–72, this signal is unambiguously seen throughout the interval with peak-to-trough amplitude of 2–3 nT. This signal was earlier identified by Gonzalez *et al.* (1993) in the spectrum of Ap and they attributed its presence to the fact that intense geomagnetic disturbances tend to occur on either side of solar maximum with an average time separation of 3 to 4 y. However, the continuous presence of this signal rules out the possibility of its association with only intense geomagnetic disturbances. Gonzalez and Gonzalez (1987) also detected a 3.7-y periodicity in the polarity of the interplanetary magnetic field direction. As sector boundary passage is a recurrent phenomenon and geomagnetic activity is known to be enhanced in association with the boundary passage (Rangarajan, 1977), it is likely that this periodicity results from corresponding fluctuations in high-speed solar wind streams. Rangarajan and Araki (1997) found an analogous (~ 44 month) periodicity in the equatorial Dst index over the interval 1957–1995. In the Dst index the signal was at its weakest in the declining phase 1972–74, while the amplitude is close to zero a little earlier with a weak oscillation during 1972–1974. It appears that the unusually strong 27-day recurrence pattern in solar wind velocity (as shown by Tsurutani *et al.*, 1995 for 1973–74) is an inhibiting factor for the detection of this periodicity. In view of the presence of this signal in the Ap, Dst and Aa indices (Delouis and Mayaud, 1975), it may be considered global in nature, affecting both the ring current and the auroral electrojets.

Approximately 16 month cycle

Paularena *et al.* (1995) identified the existence of this cycle in the post-1986 era from the dynamic FFT periodogram of the Ap index. They also state that a

similar periodicity in Ap existed around 1942. The time variations of the 16 month oscillation in the Ap index between 1932 and 1995 are shown in Fig. 8e. Unlike the 43 month and 21 month fluctuations (Fig. 8f), the temporal evolution exhibits three major bursts with the largest amplitude seen after 1986. A 1.3-y periodic oscillation was earlier identified in the solar wind velocity observations of IMP 8 and Voyager 2 during 1987–1993 by Richardson *et al.* (1994); this oscillation does not correspond to any obvious physical process of solar wind. Gazis *et al.* (1995) find that although the solar wind enhancements are more obvious nearer Earth and less so farther away, the 1.3-y variation, when present in solar wind velocity, occurred throughout the heliosphere.

Silverman and Shapiro (1983) detected a 1.4-y cycle in the visual aurora whose importance varied in a 65-y cycle with a projected minimum in 1980. The 1.3-y periodicity was prominent in both the solar wind velocity and the north-south component of IMF (in GSE) during 1988–1993 with a partial anti-correlation between the two (Szabo *et al.*, 1995). No other IMF component exhibited this periodicity. There is no evidence of the 1.3-y periodicity in earlier epochs when solar wind/IMF data was available. Bz is the only IMF component correlating well with sunspot number and hence this connection between solar wind velocity and IMF Bz strengthens the hypothesis of the solar origin of this periodicity (Szabo *et al.*, 1995).

The temporal change in amplitude of the 16 month oscillation in Ap, (Fig. 8e), is broadly consistent with the observations narrated, with the minimum near 1980 and well-defined large amplitude oscillation after 1987. If the Ap index can be considered as a proxy for solar wind velocity, then it can be said that the interval 1940–1950 would have shown similar features in the solar wind structure, as observed between 1987 and 1993 by Richardson *et al.* (1994). Years between 1964 and 1976 should also have a weaker oscillation with the same periodicity in solar wind velocity. This result is, thus, a reconfirmation of the features of the dynamic spectrum of Ap given by Paularena *et al.* (1995). But the distinct advantage of the SSA technique lies in its ability to depict the onset and termination of the enhancement of amplitude after 1940 and its time profile over the next 12 y and the secondary feeble increases between 1964 and 1980.

Approximately 21 month cycle

A quasibiennial oscillation (QBO) with an associated periodicity of 21 months is also detected as one of the spectral components (Fig. 8f). The amplitude of this signal is quite large only during the same epochs where the 16 month oscillation (Fig. 8e) is significant. Also, the isolated component is not genuinely cyclic. However, the fact that similar features of QBO were observed in the Dst index (Rangarajan and Araki, 1997), in the geomagnetic H field at several stations over the globe (Sugiura and Poros, 1977) and in the geomagnetic

disturbance field (Rangarajan, 1985) leads to the belief that this is a genuine feature of the Ap index reflecting a global phenomenon. Rogava and Shatashvili (1990) inferred a QBO in solar wind velocity from the north/south asymmetry of the cosmic rays.

Nuzhdina (1986) observed a significant QBO in Ap, Aa and Kp only at specific time intervals in a solar cycle and found it to be absent most of the other times. It was suggested that the QBO could also be a manifestation of the amplitude modulation of a carrier wave with 19 month periodicity by a solar activity cycle with a period of 10 y. If true, the Ap spectrum should have three peaks at 16.4, 19 and 22.6 months. The carrier wave frequency is absent in our results and, hence, this hypothesis is not tenable.

Since the time profiles of the 16 and 21 month oscillations of the Ap index are comparable and the source of the shorter period oscillation can be traced to the solar wind velocity unambiguously, it is tempting to suggest that QBO in geomagnetic activity is also the result of concurrent oscillations in solar wind velocity.

Thirteen month, 31 month and annual cycles

Two other 'unusual' periodicities (13 month and 31 month) observed in the Ap index are depicted in Fig. 8g, h. They are also punctuated by bursts of activity, but these are not coincident in time. Some earlier workers have indicated the presence of the periodicity around 14 month (Yacob and Bhargava, 1968; Rao and Rangarajan, 1978). While Yacob and Bhargava (1968) associated it with the solar quiet day component in H, Rao and Rangarajan (1978) thought it to be the manifestation of the Chandler Wobble periodicity. Similar to the 16 month fluctuations in Ap (Richardson *et al.*, 1994; Szabo *et al.*, 1995), this periodic oscillation waxes and wanes in bursts with the largest amplitudes centred around the maximum in solar cycle 19.

The 31 month oscillation also has its largest amplitude in the recent era similar to that was observed in the solar wind speed and IMF Bz for the 16-month periodicity. Perhaps, 31 month, 21 month and 16 month oscillations in Ap are all of solar origin but the same cannot be said of the 13 month periodicity in Ap whose temporal variation is different. This quasi-periodic fluctuation can also be identified as a subharmonic of the ~16-month periodicity. This is less likely, however, because in the methodology of SSA, individual components isolated are mutually orthogonal at lag 0.

The annual component in Ap index is shown in Fig. 8i only to highlight the fact it is mostly inconspicuous. Paularena *et al.* (1995) have noted that a one-year periodicity was evident in solar wind velocity but was absent in the southward component of the IMF during 1973–1985. In their Ap dynamic spectrum, there were few intervals, 1960, 1973–1975, 1986–1988 marked by moderate power associated with an annual variation but the power was not comparable to that of the 1.3-y periodicity between 1985 and 1990. Earlier, Bolton

(1990) detected a one-year periodicity in solar wind plasma density and velocity. We find that the annual variation in the Ap index has the largest amplitude of only about 1 unit, though some modulation of this amplitude over the time interval can be noticed. This is in sharp contrast with the annual component in Dst clearly identified by Mayaud (1978) who confirmed that it was largely due to the northward (southward) swing of the average latitude of the ring current in winter (summer) solstice, a mechanism proposed by Malin and Isikara (1976). Its absence in the Ap index corroborates their inference that the 12 month component in the Dst index is only because of the dominance of Dst stations in the Northern Hemisphere.

Conclusions

Analysis of the Kp and Ap indices of geomagnetic activity reveals that for over 6 solar cycles, the indices have retained their consistency. Yet, Ap continues to be a poor index to represent instances of extreme magnetospheric quiescence, when compared to the Am indices derived by Mayaud (1980). The occurrence characteristics of the Kp index with different magnitudes for the extended period 1932–1995 continue to replicate the major features observed earlier by Bartels (1963). Several useful tables are added, following Bartels (1963), to highlight the features of the Kp index time series over 64 years and to compare the same with that of Bartels (1963).

The time series of the occurrence frequencies of Kp representing quiet, moderately disturbed or severely disturbed conditions are analysed to bring out the nature of the solar cycle control and the presence of quasiperiodic oscillations. This analysis is extended to occurrences of specific magnitudes of Kp for several consecutive intervals to study seasonal distributions. It is shown that prolonged intervals of geomagnetic calm can be identified in all Lloyd's seasons for all years whereas a similar possibility for disturbed intervals does not exist. The dependence of the seasonal distribution of the occurrence frequencies on the phase of the solar cycle brings out the differences in the nature of the semiannual variation with smallest amplitudes seen during the ascending phase.

It is also shown that the frequency of consecutive intervals of Kp = 4–5 in the declining phase of a solar cycle could serve as an indicator of the magnitude of the solar maximum in the following cycle. The occurrence of higher geomagnetic activity (Kp ≥ 6) is directly related to the solar activity without any time lag. In contrast, moderate geomagnetic activity tends to maximise in the declining phase, indicative of at least two distinct processes such as (1) coronal mass ejections or interplanetary shocks with peak occurrence near solar maximum and (2) high-speed recurrent solar streams from coronal holes with a higher probability of occurrence in the declining phase of the solar cycle causing enhanced geomagnetic activity. Temporal changes in the semiannual variation of Ap and occurrence frequencies

of the Kp index and the lack of solar cycle dependence are brought out through the technique of complex demodulation. While the amplitudes of SAV in Ap do not show any correlation with sunspot number, they do have a moderate dependence on the magnitude of the index itself.

Singular spectrum analysis is designed to extract hidden information in a noisy series without prior knowledge of the dynamics underlying the series (Vautard *et al.*, 1992). This is applied to the series of monthly mean Ap values to bring out spectral components with significant relative contributions to the total variance. A 16-month periodicity seen initially in solar wind velocity between 1987 and 1993 by Richardson *et al.* (1994) and later both in velocity and few other IMF parameters by Paularena *et al.* (1995) in the recent years is unambiguously shown to leave its signature on global geomagnetic activity intermittantly. It is shown, corroborating Paularena *et al.* (1995), that there was perhaps only one previous era (1940–1950) when similar strong oscillations in solar wind would have been present. The presence of a ~ 44 month periodic component in Ap with almost constant amplitude throughout the years under study suggests this is related to a similar periodicity in the high-speed streams associated with sector boundary passages rather than due to the dual-peak distribution of intense geomagnetic storms as suggested by Gonzalez *et al.* (1993).

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References

- Banks, R. J.**, Complex demodulation of geomagnetic data and the estimation of transfer functions, *Geophys. J. R. Astr. Soc.*, **43**, 87–101, 1975.
- Bartels, J.**, Collection of geomagnetic planetary indices Kp and derived daily indices Ap and Cp for the years 1932–1961, *IAGA Bull.18*, IUGG Publication, 1962.
- Bartels, J.**, Discussion of time variations of geomagnetic activity indices Kp and Ap 1932–1961, *Ann. Geophysicae.*, **19**, 1–20, 1963.
- Berthelier, A.**, Influence of the polarity of the interplanetary magnetic field on the annual and the diurnal variations of magnetic activity, *J. Geophys. Res.*, **81**, 4546–4552, 1976.
- Bloomfield, P.**, *Fourier analysis of time series: an introduction*, John Wiley New York, 1976.
- Boller, B. R. and H. L. Stolov**, Kelvin Helmholtz instability and the semiannual variation of geomagnetic activity, *J. Geophys. Res.*, **75**, 6073–6084, 1970.
- Bolton, S. J.**, One-year variations in the near-Earth solar wind ion density and bulk flow velocity, *Geophys. Res. Lett.*, **17**, 37–40, 1990.
- Borello-Filisetti, O., V. Mussino, M. Parisi and M. Storini**, Long term variations in the geomagnetic activity level I: a connection with solar activity, *Ann. Geophysicae*, **10**, 668–675, 1992.
- Bravo, S. and A. L. Rivera**, The solar causes of major geomagnetic storms, *Ann. Geophysicae*, **12**, 113–120, 1994.
- Chapman, S. and J. Bartels**, *Geomagnetism*, Oxford University Press, New York, 1940.
- Childers, D. G.**, *Modern spectral analysis*, IEEE New York, 1998.
- Cortie, A. L.**, Sunspot and terrestrial magnetic phenomena 1898–1911, *Mon. Not. R. Astron. Soc.*, **73**, 52–60, 1912.
- Crooker, N. U., E. W. Cliver and B. T. Tsurutani**, The semiannual variation of great geomagnetic storms and the post-shock Russell-McPherron effect preceding coronal mass ejecta, *Geophys. Res. Lett.*, **19**, 429–432, 1992.
- Delouis, H. and P. N. Mayaud**, Spectral analysis of the geomagnetic activity index aa over a 103-year interval, *J. Geophys. Res.*, **80**, 4681–4688, 1975.
- Eselevich, V. G. and V. G. Fainshtein**, An investigation of the relationship between magnetic storm Dst index and different types of solar wind streams, *Ann. Geophysicae*, **11**, 678–684, 1993.
- Feynman, J.**, Geomagnetic and solar wind cycles 1900–1975, *J. Geophys. Res.*, **87**, 6153–6163, 1982.
- Fraser-Smith, A. C.**, Spectrum of the geomagnetic activity index Ap, *J. Geophys. Res.*, **77**, 4209–4220, 1972.
- Gazis, P. R., J. D. Richardson and K. I. Paularena**, Long term periodicity in solar wind velocity during the last three solar cycles, *Geophys. Res. Lett.*, **22**, 1165–1168, 1995.
- Gonzalez, A. L. C. and W. D. Gonzalez**, Periodicities in the interplanetary magnetic field polarity, *J. Geophys. Res.*, **92**, 4357–4375, 1987.
- Gonzalez, A. L. C., W. D. Gonzalez, S. L. G. Dutra and B. T. Tsurutani**, Periodic variations in the geomagnetic activity: A study based on the Ap index, *J. Geophys. Res.*, **98**, 9215–9231, 1993.
- Gorney, D. J.**, Solar cycle effects on the near earth space environment, *Rev. Geophys.*, **28**, 315–336, 1990.
- Gosling, J. T.**, Coronal mass ejections: the link between solar and geomagnetic activity, *Phys. Fluids B. Plasma Phys.*, **5**, 2638–2645, 1993.
- Green, C. A.**, The semiannual variation in magnetic activity indices Aa and Ap, *Planet. Space Sci.*, **32**, 297–305, 1984.
- Hapgood, M. A.**, A double solar cycle in the 27-day recurrence of geomagnetic activity, *Ann. Geophysicae*, **11**, 248–253, 1993.
- Kane, R. P.**, Power spectrum analysis of geomagnetic activity indices, *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **95**, 1–12, 1986.
- Legrand, J. -P. and P. A. Simon**, Solar cycle and geomagnetic activity: a review for geophysicists Part I: the contributions to geomagnetic activity of shock waves and of the solar wind, *Ann. Geophysicae*, **7**, 565–578, 1989.
- Malin, S. R. C. and A. M. Isikara**, Annual variation of the geomagnetic field, *Geophys. J. R. Astr. Soc.*, **47**, 445–457, 1976.
- Mayaud, P. N.**, Magnetospheric and nighttime induced effects in the regular daily variation, *Planet. Space Sci.*, **24**, 1049–1057, 1976.
- Mayaud, P. N.**, The annual and daily variation of the Dst index, *Geophys. J. R. Astr. Soc.*, **55**, 193–201, 1978.
- Mayaud, P. N.**, Derivation, meaning and use of geomagnetic indices, *Geophys. Monogr.*, **22**, AGU, Washington, 1980.
- McIntosh, D. H.**, On the annual variation of magnetic disturbances, *Philos. Trans. R. Soc. London*, **A251**, 525–552, 1959.
- Menvielle, M. and A. Berthelier**, The K-derived planetary indices: description and availability, *Rev. Geophys.*, **29**, 415–432, 1991.
- Murayama, T.**, Origin of the semiannual variation of geomagnetic Kp indices, *J. Geophys. Res.*, **79**, 297–300, 1974.
- Nevanlinna, H. and E. Kataja**, An extension of the geomagnetic activity index series aa for two solar cycles (1844–1868), *Geophys. Res. Lett.*, **20**, 2703–2706, 1993.
- Nuzhdina, M. A.**, The quasi-two year cycle in the indices of geomagnetic and solar activity, *Geomagn. Aeron.*, **26**, 663–666, 1986.

- Ohl, A. I.**, Physics of the 11 year variation of geomagnetic disturbances, *Geomagn. Aeron.*, **11**, 549–550, 1971.
- Orlando, M., G. Moreno, M. Parisi and M. Storini**, Semiannual variation of the geomagnetic activity and solar wind parameters, *Geophys. Res. Lett.*, **20**, 2271–2274, 1993.
- Paularena, K. L., A. Szabo and J. D. Richardson**, Coincident 1.3-year periodicities in the ap geomagnetic index and the solar wind, *Geophys. Res. Lett.*, **22**, 3001–3004, 1995.
- Priester, W. and D. Cattani**, On the semiannual variation of geomagnetic activity and its relation to the solar corpuscular radiation, *J. Atmos. Sci.*, **19**, 121–126, 1962.
- Rangarajan, G. K.**, Response of low latitude geomagnetic activity to sector boundary passage, *Planet. Space Sci.*, **25**, 465–471, 1977.
- Rangarajan, G. K.**, Quasi-biennial oscillation in geomagnetic disturbance field, *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **94**, 29–34, 1985.
- Rangarajan, G. K.**, Indices of geomagnetic activity in *Geomagnetism vol. 3*, Ed. J.A. Jacobs, pp 323–384, Academic Press, London, 1989.
- Rangarajan, G. K. and Araki, T.**, Multiple timescales in the fluctuations of the equatorial Dst index through singular spectrum analysis, *J. Geomagn. Geoelec.*, **49**, 3–20, 1997.
- Rao, D. R. K. and G. K. Rangarajan**, The pole tide signal in the geomagnetic field at a low latitude station, *Geophys. J. R. Astr. Soc.*, **53**, 617–621, 1978.
- Richardson, J. D., K. I. Paularena, J. W. Belcher and A. J. Lazarus**, Solar wind oscillations with a 1.3-year period, *Geophys. Res. Lett.*, **21**, 1559–1560, 1994.
- Rogova, O. G., and L. K. Shatashvili**, Quasiperiodic 2-year variation in cosmic rays, solar activity, solar wind and geomagnetic activity, *Geomagn. Aeron.*, **30**, 482–484, 1990.
- Rotonova, N. M., N. E. Papitashvili, A. N. Pushkov and V. H. Fishman**, Spectral-statistical spatial analysis of 60- and 30-year geomagnetic field variations and conductivity of the lower mantle, *Ann. Geophysicae*, **3**, 225–238, 1985.
- Russell, C. T.**, Geophysical coordinate transformations, *Cosmic Electrodyn.*, **2**, 184–196, 1971.
- Russell, C. T. and R. L. McPherron**, Semiannual variation of geomagnetic activity, *J. Geophys. Res.*, **78**, 92–108, 1973.
- Sargent, H. H. III**, The 27-day recurrence index in “*Solar wind magnetosphere coupling*”, Ed. Y. Kamide and J.A. Slavin, pp.143–148, Terrapublishers, Tokyo, 1986.
- Sargent, H. H.**, Recurrent geomagnetic activity: evidence for long-lived stability in solar wind structure, *J. Geophys. Res.*, **90**, 1425–1428, 1985.
- Sharma, A. S., D. Vassiliadis and K. Papadapoulos**, Reconstruction of low dimensional magnetospheric dynamics by singular spectral analysis, *Geophys. Res. Lett.*, **20**, 335–338, 1993.
- Silverman, S. M. and R. Shapiro**, Power spectral analysis of auroral occurrence frequency, *J. Geophys. Res.*, **88**, 6310–6316, 1983.
- Sugiura, M. and D. J. Poros**, Solar-generated quasi-biennial geomagnetic variation, *J. Geophys. Res.*, **82**, 5621–5628, 1977.
- Szabo, A., R. P. Lepping and J. H. King**, Magnetic field observations of the 1.3-year solar wind oscillation, *Geophys. Res. Lett.*, **22**, 1845–1848, 1995.
- Taylor, J. R., M. Lester and T. K. Yeoman**, A superposed epoch analysis of geomagnetic storms, *Ann. Geophysicae*, **12**, 612–624, 1994.
- Taylor, J. R., M. Lester and T. K. Yeoman**, Seasonal variations in the occurrence of geomagnetic storms, *Ann. Geophysicae*, **14**, 286–289, 1996.
- Tsurutani, B. T. and W. D. Gonzalez**, On the solar and interplanetary causes of geomagnetic storms, *Phys. Fluids B. Plasma Phys.*, **5**, 2623–2630, 1992.
- Tsurutani, B. T., W. D. Gonzalez, A. L. C. Gonzalez, F. Tang, J. K. Arabello and M. Okada**, Interplanetary origin of geomagnetic activity in the declining phase of the solar cycle, *J. Geophys. Res.*, **100**, 21717–21733, 1995.
- Vautard, R. and M. Ghil**, Singular spectrum analysis in non linear dynamics with application to palaeoclimatic time series, *Physica D35*, 395–424, 1989.
- Vautard, R., P. Yiou and M. Ghil**, Singular spectrum analysis: a toolkit for short noisy chaotic signal, *Physica D58*, 95–126, 1992.
- Wilson, R. M.**, On the level of skill in predicting maximum sunspot number: a comparative study of single variate and bivariate precursor techniques, *Solar Phys.*, **125**, 143–158, 1990.
- Yacob, A. and B. N. Bhargava**, On 26-month periodicity in quiet day range of geomagnetic horizontal force and in sunspot number, *J. Atmos. Terr. Phys.*, **30**, 1907–1911, 1968.